APPLICATON OF SGC-RP TECHNIQUE FOR DEVELOPMENT OF HYDRODYNAMIC MODELS

by

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MASTER OF TECHNOLOGY

by

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CERTIFICATE

This is to certify that the work contained in the thesis entitled, "**Application of SGC-RP technique for development of hydrodynamic models**" has been carried out by K.R.Arvind kumar (Roll No. 9710508) under our supervision and that this work has not been submitted elsewhere for a degree.

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K.R.Arvind Kumar

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NOMENCLATURE

P_d	Discharge pressure of a pump (N/m^2)
P_s	Suction pressure of a pump (N/m^2)
C_d	Discharge velocity of a pump (m)
C_s	Suction velocity of a pump (m)
H	Total head (m)
h_g	Vertical distance between pressure tapping for suction and delivery Gauge (m)
Q	Discharge (m^3/s)
P	Power input to impeller (w)
P_m	Power input to motor (w)
N	Pump speed (rpm)
N_S	Specific speed
η	overall efficiency of pump
η_m	Motor efficiency
ω	Specific weight (N/m^3)
β	Impeller discharge angle

ABSTRACT

Rapid prototyping is a relatively new technology that transforms 3D CAD data into physical prototypes by adding material layer by layer. Cubital's Solid ground curing (SGC) is a high-end liquid based RP system with some unique capabilities such as high throughput, ability to produce assemblies and ability to produce completely cured parts without any special support structure. In the present work, the process parameters of the newly installed SGC system at CAD-P lab, IIT-Kanpur has been studied extensively for producing quality prototypes from the system.

The main applications of RP models is concept verification, form and fit testing and as a pattern for tooling. Functional testing of RP models has not been widely reported because of the limitations of material properties; RP systems do not have the capability of producing metallic prototypes. If RP has to gain more widespread acceptance, applications in the direction of actual testing need to be explored.

One of the prospective applications of RP models is hydrodynamic testing. In the present work, the feasibility of using RP models for centrifugal pump testing has been examined. RP impellers were created from CAD models of actual impellers of pumps using the Cubital's RP system. Performance tests were carried out on two low head pumps for comparing the characteristics of RP impeller with metal impeller. The results have been quite encouraging in that the characteristics of RP impeller matched with those of metal impellers. FEA of the impeller has also been carried out to determine the maximum stress developed in the impeller under the pump test conditions. The limiting pump test condition for the RP impeller has been formulated on the basis of FEA.

Chapter 1

INTRODUCTION

1.1 Introduction

As we step into the 21^{st} century, the world is getting shrunk into a global village and there is more competition than ever before in the engineering industry. The consumer is more demanding, he wants quality products at low prices in real quick time. So the producers have to bring out new, improved products in a short time to stay in business. It is this situation that has spawned "*Time compression technologies*", a breed of technologies which help shorten product development time.

CAD/CAM has significantly improved traditional design and manufacturing practices. Computer aided design (CAD) involves creating geometric models of conceptual design and analyzing the design through tools like Finite element analysis (FEA). Computer aided manufacturing (CAM) essentially involves generation of cutter location data file from CAD database and feeding the data to a numerically controlled (CNC) machine tool. "*Virtual prototyping*" which is visualizing and testing CAD models on a computer helps in initial design iterations, but a physical prototype has to be tested to validate the design. Traditional manufacturing methods like casting, forming, machining are time consuming. It is in this context that a new exciting class of technology called "*Rapid prototyping*" comes into picture, which promises to speed up the product development process.

1.2 Rapid Prototyping – An Overview

The term Rapid prototyping refers to a class of new manufacturing technologies, which produce models from CAD data layer by layer in an additive way. RP processes do not use conventional tools or fixtures, instead the prototype is produced by solidifying photosensitive polymers, sintering powders or cutting sheets using media like lasers, UV light etc. RP is an "*additive*" process since it does not involve removal of material like machining. It is referred to as "*Layered manufacturing*", since the 3-D part is produced by adding one layer on top of the

other. It is also referred to as "*Solid free form fabrication*" because of its ability to produce intricate shapes with little constraint on form. It has been termed as "*Desk top manufacturing*" because it can be set up in Office environment beside the CAD stations.

1.2.1 RP Process chain

All RP systems have a similar sort of process chain consisting of Five steps [1]. Such a generalized process chain is shown in fig.(1.1)

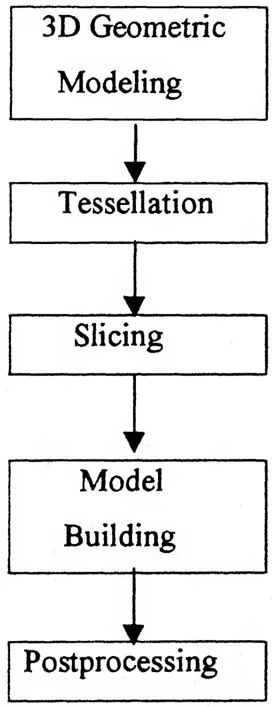


Fig (1.1) RP process chain

The first step in the process chain is 3-D geometric modeling. A solid model of the part to be produced is created on a CAD system. The solid model is then tessellated, wherein the surfaces of the model are approximated by polygons. The RP industry standard for tessellation is '. STL ' format (after StereoLithography of 3D Systems). The .STL file consists of a list of triangular facets representing the outside skin of the object.

The computer analyses the .STL file that defines the model and mathematically slices it into a series of parallel cross-sections. The model is then built on the RP machine by systematic stacking of the layers one above the other through

solidification of liquids, sintering of powders or gluing of thin laminations. Post processing involves removal of support material, post curing or finishing by sanding and painting to improve surface finish and aesthetic appearance of the part.

1.2.2 Classification of RP systems

RP systems are classified according to the initial form of material used for building models. They are categorized into liquid based, solid based and powder based RP systems.

a) Liquid based RP systems

In liquid based RP systems the model material is initially in liquid state. The liquid is usually a photocurable resin, which is solidified by photopolymerisation either by laser or UV light. The two important liquid based RP systems are *StereoLithography* (SLA) of 3D systems, Inc and *Solid ground curing* (SGC) of Cubital, ltd.

b) **Solid based RP systems**

Solid based RP systems include all forms of material in solid state except powder. The material can be in the form of a wire, roll, laminates or pellets. The two important solid based RP systems are *Fused Deposition Modeling* (FDM) of Stratasys, ltd. And Helisys' *Laminated object manufacturing* (LOM).

c) Powder based RP systems

In powder based RP systems the initial state of the material is granular powder. There are a number of powder based RP systems which differ essentially by the method employed to bind one layer of powder to another. Some systems employ a Laser while others use a binder/glue to achieve the joining effect. DTM's *selective laser sintering* (SLS) is the well-known powder based RP system.

1.2.3 Advantages and restrictions of RP technology

The benefits of RP technology are many. RP reduces time to market drastically. This is because prototypes can be produced in a matter of hours or days

without having to make tools, fixtures, cores or patterns. In fact if properly integrated into the product development process, RP could result in savings in time and cost ranging from 50 to 90 percent depending on the size of production. [3]. With RP there are almost no limitations of geometrical complexities, the designer can optimize part design with little manufacturing restrictions like tool accessibility, draft angles, parting lines etc. Sculptured shapes, intricate internal details and thin walled parts can be accommodated.

The main restriction in RP is the inadequate physical characteristics of the materials. As of today, RP systems do not have the capability of producing metallic prototypes. This implies limitation in engineering testing and analysis. Parts produced by RP have accuracy and surface finish inferior to those made by machining. Also the cost of RP machines and materials should come down if they are to become viable for small and medium sized companies.

1.3 Applications of RP models

RP models find application in various stages of product development such as Design, Analysis, Planning, Manufacturing and Marketing.

a) Applications in Design and Engineering analysis

1) Visualization and Design verification

Though 3D CAD images improve visualization compared to blue prints, it is still difficult to visualize exactly how a complex object looks like until a physical object is produced. The touch of physical objects can reveal unanticipated problems and sometimes spark a better design. With RP, prototype of even a complex part can be built quickly, so design can be evaluated in a short time.

2) *Form and Fit*

The form of the RP model can be evaluated from both aesthetic and functional standpoint. Fitment of a complicated assembly can also be verified by producing various components of assembly. Clearance and interference between the components of an assembly can be checked.

3) *Flow analysis*

RP models can be tested for air and water flow analysis. Since the same CAD data of the model is used in software tools for flow analysis and RP, modified model

can be generated again using RP very much faster than traditional methods. Examples of flow analysis include manifolds of engines, aerodynamic models and pumps.

4) Stress *analysis*

Since many of the RP systems produce transparent or translucent models, they can be used for photo-optical stress analysis to determine stress distribution in the product.

b) Applications in Manufacturing and Tooling

1) Soft tooling applications:

RP models can be used as master patterns for soft tooling techniques such as silicone rubber vacuum casting, spray metal tooling, epoxy tooling etc. The moulds produced by these techniques can be used to produce a limited number of plastic parts.

2) Hard tooling applications:

Traditional ways of making patterns for Dies and moulds are time consuming and require highly skilled labour. RP can produce patterns for processes like sand casting accurately and quickly. Also wax patterns can be directly produced by some RP systems which can be used in investment casting.

3) Copy milling:

RP parts can be used as master models for copy milling metallic parts, wherein the form of the master model would be reproduced on the workpiece being milled.

c) Marketing applications:

A prototype can be used to demonstrate a concept, a design idea as well as the company's ability to produce it. Also the prototype can be used to gain customer's feedback for design modifications so that the final product will meet customer requirement.

The industries being catered to by RP at present include Aerospace, Automotive, Biomedical, consumer goods, jewelry, electrical, electronics etc.

1.3 Centrifugal pump design – A state of practice

Although historically pumps are among the oldest forms of machines, still relatively little is known about the complex flow phenomena inside them. The approach in pump design is relatively empirical and it is impossible even now to design a pump having a precisely determined hydraulic performance over it's full working range [9].

The design of a pump impeller begins by selecting the rotational speed to meet the given head-capacity conditions. This establishes the specific speed or type of the impeller. The designer then looks for a suitable "model" from existing impellers of the same specific speed, which has satisfactory hydraulic performance. The reduction factor to be applied to the existing model is found by the use of affinity laws.

To design a new impeller, for which no model is available, experimentally established "Design factors" from successful designs are used. These factors give direct relationship between the total head and capacity at the design point and several elements of Euler's velocity triangles. The impeller profile and vane layout is drawn once the following elements are known: Meridional velocities at inlet and outlet, Impeller outside diameter, and vane inlet and outlet angles.

The vane shape layout for blades with single curvature is simple as all fluid particles enter and leave the impeller at the same diameter. The vane shape is generated by using methods like circular arc method, point by point method and conformal representation method [9]. When making the pattern, the shape of the blade is usually transferred by means of templates or by pricking through from the drawing.

The vane shape layout is more complicated for blades with double curvature, because vane angles vary along the radius and several streamlines have to be considered. Three streamlines suffice for a majority of cases, along the front and back shrouds and third one equally spaced from both the shrouds. The vane shape is drawn by using either the point by point method or the conformal representation method. Several equally spaced sections are taken perpendicular to the impeller axis and the contour lines of the vanes at each of the sections are drawn.

The pattern maker cuts boards of approximate thickness according to the contours. Then the boards are stacked in a proper order, glued and corners of the

boards are shaved off to give a smooth surface to the blade. When designing impellers of small width, determination of contour is unnecessary. For this a block of wood is taken and excess material is cut away according to templates based on shape of curve on meridional section and front and back shrouds.

There are two methods for making the casting moulds [10]. In the first method, a sectional core box is made for a single vane channel. For making this, views of the front and backsides of the vanes are sufficient. A number of cores equal to the number of vanes are made and assembled into one core for the whole impeller.

In the second method, one core is made for the whole impeller. A wooden vane is first made by gluing together the vane sections, from which metal vanes are cast for the core box. The core is baked with metal vanes in place and is then broken to remove the vanes, after which the parts of the core are pasted together. In another method, the lost wax process the blades are made of a mixture of paraffin or wax and chalk. As the mould is heated, the blades melt and run out of the mould leaving free spaces for the metal.

The prototype is obtained by casting the mould. The impeller is then tested on a pump and the parameters such as Discharge, Head, Power consumption and efficiency are found out. Characteristic curves are drawn to verify the performance of the pump at the required operating conditions. Any discrepancy between the required and obtained results would necessitate further design modifications and testing.

The traditional way of making the impeller prototypes is time consuming and requires high degree of skill. So it is not possible to do quick design iterations and test the performance of the impellers. Thus faster methods of producing impeller prototypes need to be explored.

1.4 Statement of the problem

Rapid prototyping is a new, exciting technology making forays into industries as well as academies. Cubital's Solid ground curing (SGC) is a high-end RP system with some unique capabilities such as the ability to produce assemblies, high throughput, no post-curing etc. The first objective of the present work is tó establish the SGC system at IIT-Kanpur and study the process parameters for producing quality prototypes from the system.

RP models find application in various industries like aerospace, automotive, consumer goods etc. Still application areas like hydrodynamic analysis have not been explored fully. Design of centrifugal pump involves extensive testing of impellers. Traditional methods of producing prototypes of impellers through pattern making and casting is a cumbersome process, which is time consuming and requires high degree of skill. RP can produce impeller models quickly and accurately from the CAD model of the impeller. The goal of the present work is to examine the feasibility of using the RP models for centrifugal pump testing. It is proposed to conduct performance tests on pumps with actual metal impeller and with RP impeller. One aspect to be examined is the ability of the RP model to withstand the pump forces and the other is the faithfulness of the vane geometry to give the same performance characteristics as the metallic impeller. The limiting operating conditions of the RP impeller are aimed to be found out by Finite element analysis.

1.6 Organization of Thesis

The thesis consists of six chapters. The organization of the thesis is as follows.

CHAPTER 1 gives an overview of Rapid Prototyping technology and existing practices in the design of centrifugal pumps.

CHAPTER 2 gives the technical details about the Solider 4600 rapid prototyping system and the model building procedure.

CHAPTER 3 gives a background about centrifugal pump characteristics, Model tests and similitude and pump testing principles.

CHAPTER 4 gives the approach used in CAD modeling of impellers, pump testing procedure and FEA procedure

CHAPTER 5 consists of results and discussions.

CHAPTER 6 summarizes the findings and suggests scope for future work.

Chapter 2

SGC RP PROCESS

2.1 Principle of operation

The Solid ground curing (SGC) process involves selective solidification of photo sensitive resin layers by ultra violet light successively to produce the rapid prototype model. The SGC process is patented by *Cubital, ltd. Israel* and is employed in *Cubital's Solider 4600* and *5600* Rapid prototyping systems.

The principle of operation is shown in fig.(2.1). The SGC process consists of two cycles, the *mask generation cycle* and the *model building cycle*, which are performed simultaneously to produce the models.

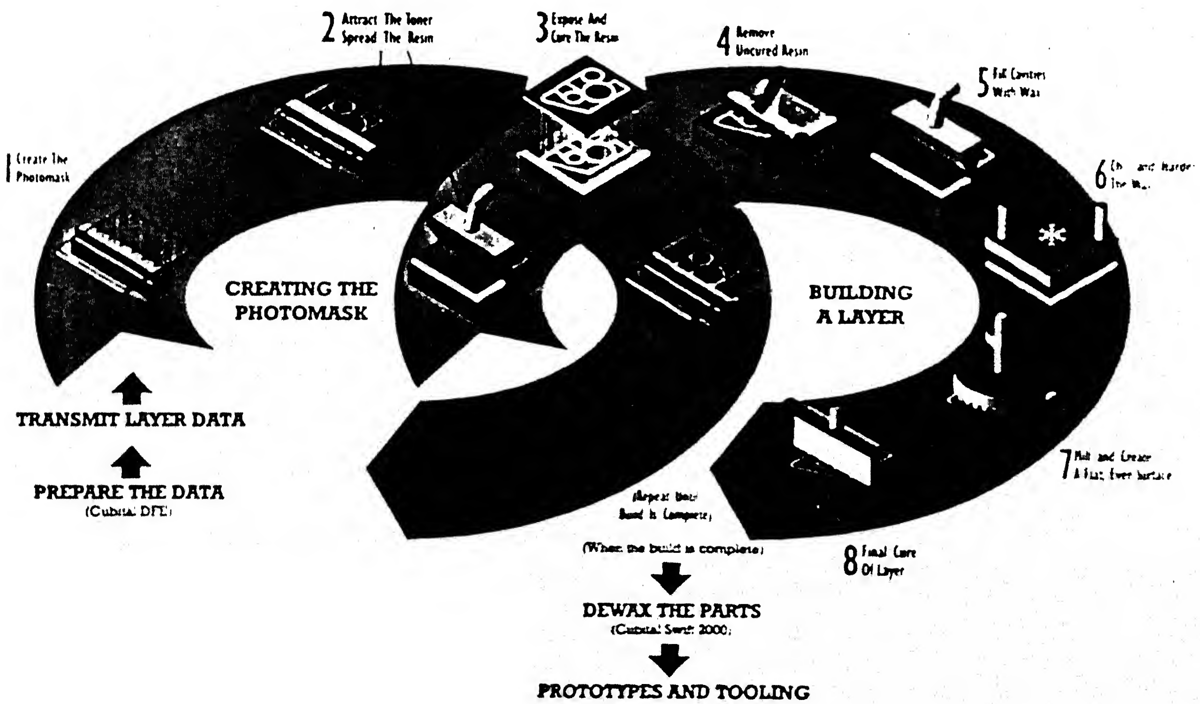


Fig (2.1) SGC Process - Principle of operation

The CAD files of the models to be produced are sliced into thin layers and submitted to the machine. The machine's imaging station creates an optical mask of

the layer. The image creating process is similar to that of a photocopy machine. An ion cartridge charges areas, which constitute negative of the layer definition on a Mylar sheet coated glass plate. The image is developed with electrostatic toner. This results in a mask of black (toner) and transparent (no toner) areas.

Meanwhile a thin layer of photopolymer resin is spread across the model table. The photomask and the model table are aligned under an UV lamp. The UV light is turned on for a few seconds and the part of the resin exposed to the UV light under the photomask is hardened through photopolymerisation. Areas covered by the mask are unexposed and remain in liquid form. The toner particles are erased from the glass plate and the charges are removed so that the next mask can be developed.

The uncured resin is wiped from the worktable with an aerodynamic wiper and vacuum nozzle. The worktable again moves under the UV light for secondary exposure (without mask) so that the layer is completely cured. A layer of hot wax fills the cavities left by the wiped liquid resin. At the next station, a cooling plate cools and solidifies the wax. The wax acts as a support structure for the parts. Finally the layer is milled down to a flat surface of predefined thickness which is about 150 microns.

A layer of resin is again spread over the surface, the next photomask is developed and the steps are repeated until all the layers are built. After production the wax slab with embedded resin parts is taken out. The water soluble wax is dissolved in warm acidic water to get the models.

2.2 SYSTEM ARCHITECTURE

The solider 4600 system consists of several components that work in unison to produce a model. Some of these components take part in Data processing while the others aid in model building. The main components of the Solider 4600 system are shown in fig.(2.2)

The Data front end (DFE) workstation reads and checks the CAD data files, makes modifications and corrections when necessary and prepares them for production. It slices the objects of the CAD files into thin layers and submits the layer data to Model production machine (MPM).

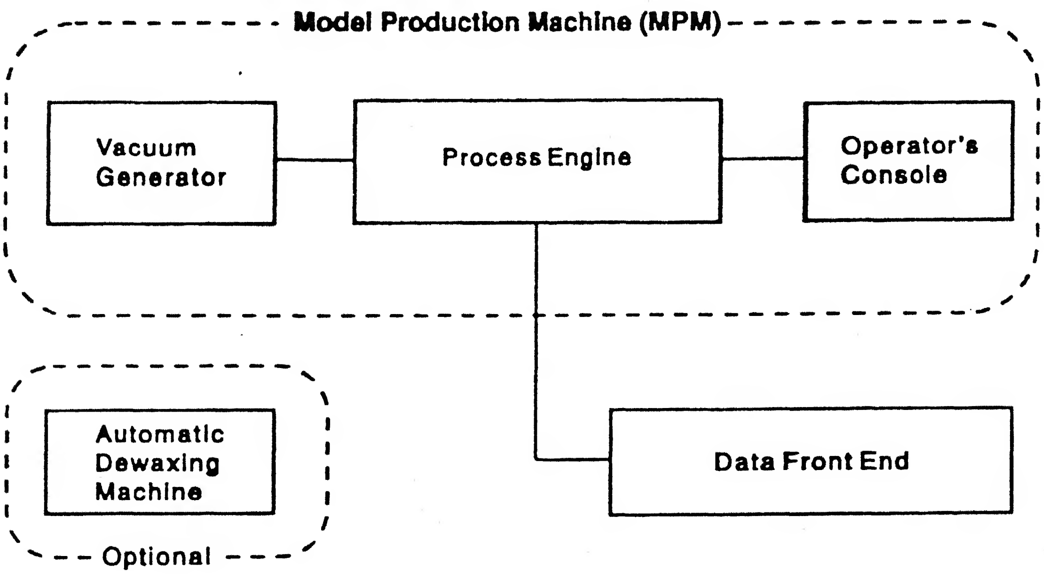


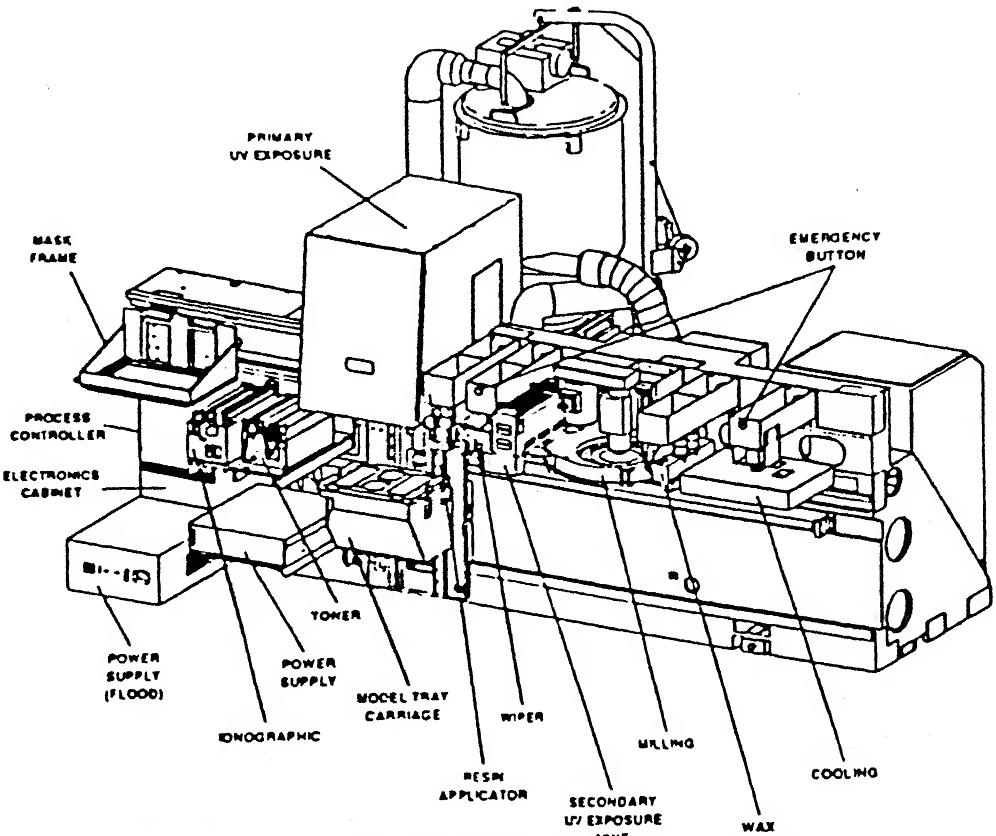
Fig (2.2) Solider 4600 Block diagram

The MPM consists of the process engine, operator's console and vacuum generator. The process engine consists of a heavy frame onto which are mounted the functional units that participate in the steps of mask generation and model building cycles.

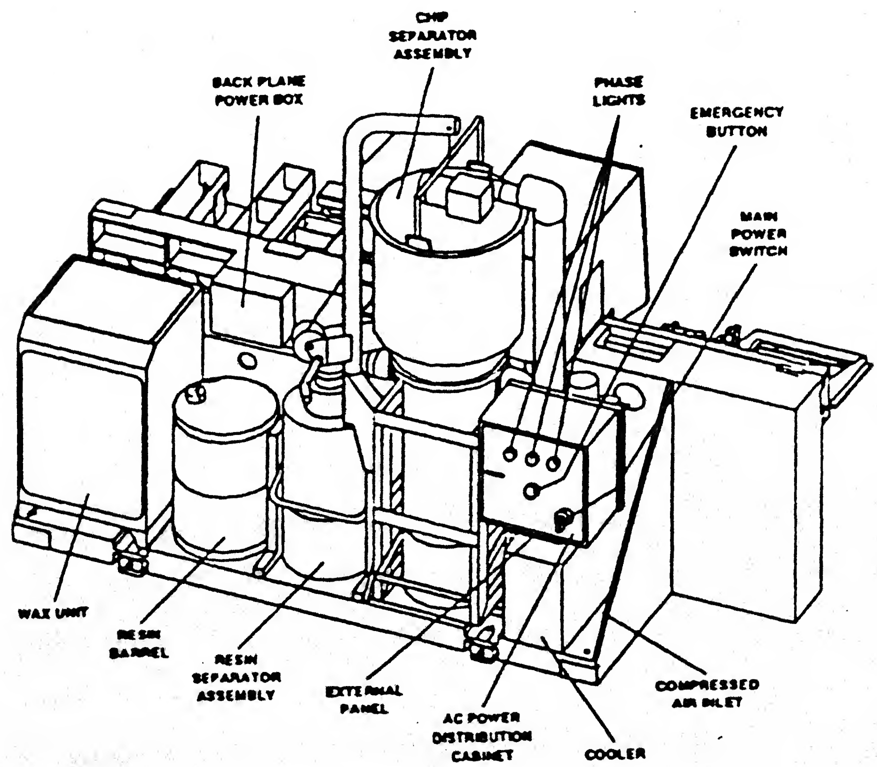
The operator uses the operator's console to control the model building process. The vacuum generator provides the vacuum pressure that alternately removes the uncured liquid resin and the plastic chips from the milling operation. The automatic dewaxing machine is an optional stand-alone unit that quickly removes the filler wax from the workpiece. The wax is dissolved by spraying a warm citric acid solution through moving nozzles onto the model.

2.2.1 FUNCTIONAL UNITS

The solider 4600 is a complex system with a number of functional units operating in a coordinated fashion to produce the models. Some of the units take part in mask generation and the others in model production. All the functional units are mounted on the process engine as shown in fig. (2.3a) and fig. (2.3b)



(a) Front View



(b) Back View

Fig.(2.3: Solider 4600 System Front view and Back view

2.2.1.1 MASK GENERATOR UNITS

The mask generator receives the layer data from the DFE and produces a mask, which determines the shape of the next layer to be added to the model. The mask generator units are located in the left half of the process engine in fig. (2.3a)

The mask generator consists of the following units.

1) **Motion units:** The motion units move the mask from one station to the next. They consist of the motion track to guide the maskframe, Motion drives, bumpers and switches.

2) **Mask unit:** The mask unit consists of a metal-coated glass mounted on the mask frame. A transparent Mylar sheet is glued over the glass on which the mask is generated.

3) **Ionographic unit:** The Ionographic unit neutralizes charges of the previous layer and creates an electrostatic image of the next layer on the Mylar sheet. The major component of the Ionographic unit are

a) *Erase rod*: The erase rod discharges residual charges from the Mylar sheet. There are six wires of which one is active and the other five are spares.

b) *Ion cartridge*: The ion cartridge jets ions onto the Mylar sheet creating an electrostatic image of the next layer. Holes in the upper surface of the cartridge are fired in a pattern determined by the information received from the process controller.

c) *Air shield*: The air shield maintains a flow of air across the top of the ion cartridge to protect it from contamination by toner powder.

4) **Toner unit**: After primary UV exposure, the toner unit wipes toner from the Mylar sheet, thereby erasing the previous mask. After the next image is charged on the sheet, toner is attracted to the charged areas creating mask for the next layer. The toner unit consists of the following major components.

a) Cleaning blade, which erases the previous layer on the Mylar sheet.

b) Brush roller, which rotates against the cleaning blade and cleans it.

c) Develop roller, which is a rotating magnetic roller on which toner collects before being attracted to the Mylar sheet.

4) Power supply unit: The power unit consists of high and low voltage power supplies and station card, which links the mask generator units to the process controller.

2.2.1.2 MODEL BUILDER UNITS

The model builder units take part in model building cycle. The major units of the Model builder are:

1) Motion units: The motion units move the model tray from one station to the next. The motion unit consists of the following components:

a) Model tray: The model tray provides a base for building the model. The tray consists of a PVC plate bolted to a metal plate for support.

b) Model tray carriage: The carriage supports and moves the tray horizontally and vertically along the carriage tracks.

c) Motion drives: The motion drives use motors to turn ball screw to move the model tray carriage in the horizontal and vertical direction. Encoders linked to the process controller monitor the motion.

d) Switches: Switches located on the tracks alert the process controller when to activate steps in model building.

2) Resin unit: The resin unit pumps liquid resin from a storage barrel into the resin applicator, heats the resin for achieving optimum viscosity and spreads a thin, uniform layer of liquid resin about 200 microns thick over the model tray. The major components of the resin units are:

a) Resin pump and Air bleeder: The resin pump pumps resin from the resin barrel to the resin applicator. During bleed cycle, the resin pump directs the resin through an air bleeder back to the barrel. The bleed cycle prevents air bubbles forming in the resin layer.

b) Resin applicator: The resin applicator heats and spreads resin onto the model table. It consists of a resin heater, which maintains the temperature of resin for optimum viscosity at about 32 degree Celsius, and a resin dispenser which forces the

resin through a narrow slit. The applicator positioner lowers the applicator downward while spreading and raises it when idle.

3) UV exposure unit: The UV light selectively polymerizes the resin layer by exposure of UV radiation through the mask. The main components are:

a) UV lamp: A magnetron generates microwave energy, which is directed to a Quartz bulb. The quartz bulb gets heated by the waves and emits the UV radiation.

b) Shutter: The shutter is pneumatically activated to control the exposure time of the resin to UV radiation.

c) Hood: Hood is a protective cover to isolate the surrounding environment from UV radiation.

4) Wiping unit: After the primary UV exposure, the wiping unit removes the unsolidified liquid resin from the model surface. The major components of the wiping unit are:

a) Air blower and slit: The air blower produces a thin, powerful stream of air to lift liquid from the surface and directs it towards the suction slit.

b) Collector blade and suction slit: The collector blade scoops up the rolling wave of resin and guides it into the slit opening. The vacuum pressure present at the slit carries the resin into the resin separator.

c) Resin separator: The resin separator located in-line between the slit and vacuum manifold separates the liquid resin from the air stream. It consists of a filter, which removes the resin droplets from the air stream and a collector, which collects the separated resin for removal.

5) Wax unit: After the unsolidified resin is wiped away, the wax unit spreads a layer of liquid wax approximately 300 microns thick across the model tray surface. The wax covers the hardened resin and fills in voids to support the model structure. The major components of the wax unit are:

a) Wax melter: The wax melter melts blocks of solid wax and passes the liquid wax to the wax tank.

b) Wax conditioner tank: The tank stores wax for spreading. A stirrer continuously stirs the wax. The temperature of the liquid wax is maintained at about 65° C through closed loop heating control. Level sensors notify the process control if the wax level drops below the lower level or exceeds the upper level.

c) Wax pump and filter: The wax pump forces liquid wax from the wax tank to the wax applicator through a filter and a heated insulated hose.

d) Wax applicator: The wax applicator receives wax under pressure from the pump and spreads it on the model tray. The wax applicator consists of two wax guns, which are pneumatic pistons that rapidly move down to force wax through the wax spreading slit. An applicator positioner lowers the applicator downward by about 2 mm for spreading and raises it when idle.

6) Cooling unit: The cooling unit rapidly cools and solidifies the wax layer. The major components of the cooling unit are:

a) Cooling plate: It consists of an outer box and an inner box. The inner box contains recirculating chilled water at about 4° C. When the model tray comes under the cooling plate, a piston moves the inner box downwards, the inner box presses the outer box against the model tray surface and solidifies the wax.

b) Cooler: the cooler chills the water to 4° C and circulates it through the inner box.

7) Milling unit: The milling unit mills the last layer of solid wax and hardened resin to a thickness of about 150 μm. The major components of the milling unit are:

a) Milling plate: It consists of 30 diamond tipped cutters that are mounted on the underside of the plate.

b) Milling vacuum hood: The hood removes the milling chips and dust from the space surrounding the model tray.

c) Chip separator: The separator located in-line between the milling hood and vacuum manifold separates the milling chips from the air stream to collect them for disposal. It consists of a filter, which is a special fabric suspended in a metal-ribbed cage. A filter shaker vibrates the filter so that the chips sticking to the filter fall into the chip drum. The chip drum retains the separated chips for disposal.

8) Vacuum unit: The vacuum unit generates vacuum used by the wiper and milling units. The major components of the vacuum unit are:

a) Vacuum generator: This generates a strong vacuum using an electric motor, which drives a large turbine. The vacuum generator is a stand-alone unit, which delivers the vacuum to the vacuum manifold of the process engine.

b) Vacuum manifold: The manifold switches the vacuum source to either the resin separator to suck the liquid resin or the chip separator to remove the milling chips at appropriate time in the cycle.

2.3 DATA FRONT END (DFE)

The data front end is an interface between the CAD files and the model production machine (MPM). It is the software, which prepares the file data for actual production.

The DFE accepts CAD data files in a variety of formats and transforms them into a format that is compatible with Solider. It enables the user to check the CAD files for flaws, correct flaws, remove redundant information and generate more efficient 3D representations of objects before production. It has tools for duplicating, moving, rotating parts and nesting a number of parts within the 500 x 350 x 500-mm work volume. In DFE terminology, an object to be produced is referred to as an 'actor' and the volume of objects for a production run as 'show'. Once the parts to be produced are organized, the DFE slices the files into thin layers and submits the layer definitions to the MPM.

The DFE has four applications that perform the tasks mentioned above.

1) Reception

2) Academy

3) Show

4) Production

The DFE work flow is shown in fig.(2.4)

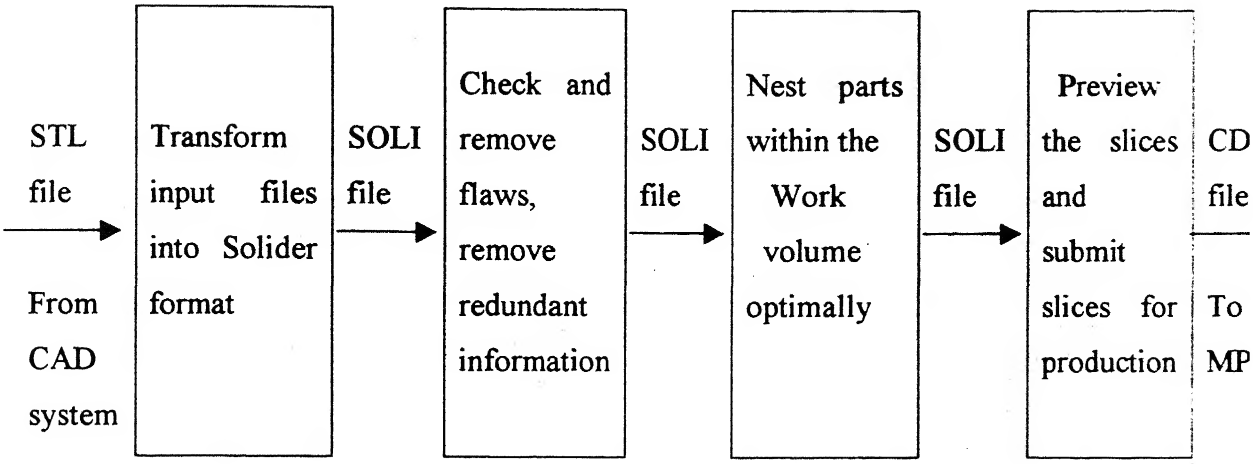


Fig (2.4) DFE work flow

2.3.1 RECEPTION

Reception is the solider application for enrolling CAD files and transforming them into a format suitable for Solider 4600.

The input files may be in either STL (ASCII or Binary) format, which is the standard RP format or Cubital's CFL (Cubital facet list) format. Other input formats such as VDA 2.0 and DXF can be first converted into CFL format using command line applications and then used in Reception. The output file, which is in Solifile format, is generated only if the input files are valid and not corrupt.

Reception can also be used for converting soli files back to STL or CFL files.

2.3.2 ACADEMY

Academy is the DFE application, which enables repair of flawed soli files and improvement of an actor's physical characteristics.

Academy comes into picture only if the input STL file is corrupt. Generally, high-end CAD systems such as Pro/E, I-DEAS produce good solid models and hence valid STL files. After reception an actor is passed through the academy. The academy displays the flaws in the actor, if present. The flaws can then be repaired using the tools of the Academy. If the actor does not contain any flaws, it can be taken to the show directly.

The tools under Academy can be grouped as:

1) Editing tools
2) Correction tools
3) Compression tools

1) Editing tools: Editing tools enable manipulation of actors like transformations and cutting. The options available under editing are:

a) Geometrical transformations such as rotation and scaling if the actors and changing the units of the actors.

b) Model cutting: This function can be used to cut an object into pieces. The pieces are stored in separate files and the original actor remains intact. This option can be used to decrease the height of the production run, wherein the object can be produced in parts and glued back later.

c) Model widening: This function creates a volume from a surface by offsetting the surface through the required distance and then connecting the duplicate surface to the original with facets.

d) Surgery: This option is used to manipulate the items of an actor. Item is a part of an actor that does not touch any other part because it's facets do not have neighbours in other parts. The items of an actor can be separated into different files or deleted.

2) Correction tools: These tools can be used to correct flaws in the actor.

A flaw is defined as a closed contour, which is an area of discontinuity of the boundary of the polyhedron. The academy recognizes five different types of flaws – Border, crack, crack connected to border, triangular and degenerate flaws.

When an actor is opened in the Academy, the number and types of flaws are displayed of the actor contains any flaws. These flaws can be corrected by using the following functions from the clinic menu.

a) Patch: This function is used to repair flaws resulting from missing facets. The opening is closed by stitching with a series of triangular facets as shown in fig (2.5)

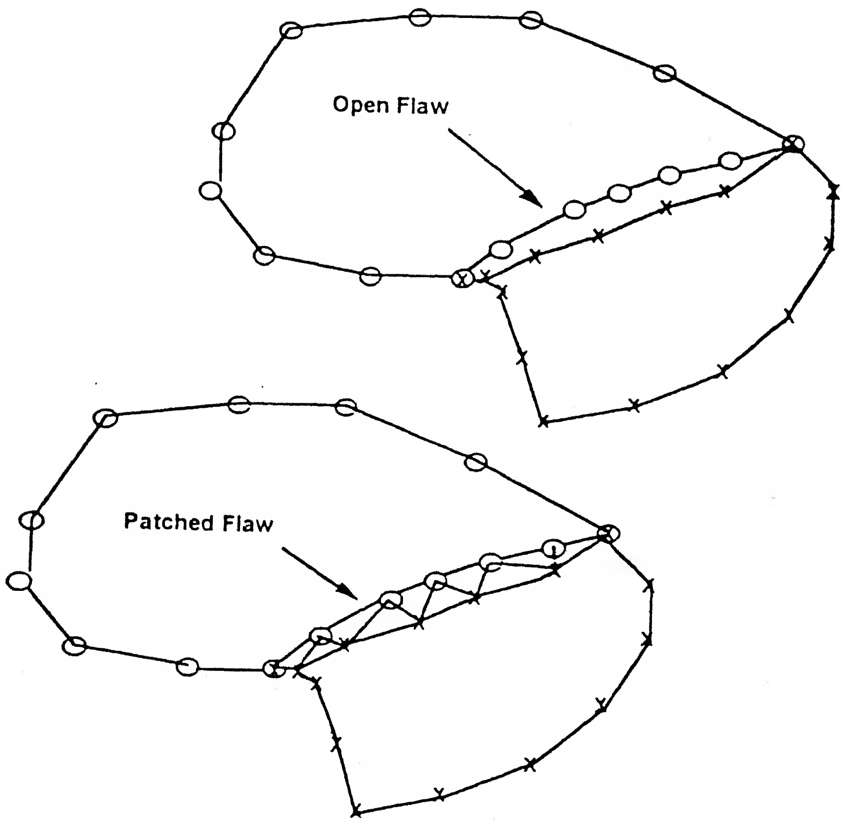


Fig (2.5) Patch function

b) Bind: This function is used to connect gaps appearing along the border of the items. Pairs of borders are connected with a series of triangles maintaining a specified maximum gap.

Also, faulty directions of facet normals can be corrected using the order polygons option of improvements menu.

3) Compression tools: Compression tools are used to remove redundant information and decrease the size of the files.

a) Diet: This option unites the vertices within a minimum specified distance. This is used to reduce the accuracy of point information of the object without adversely affecting the polyhedral representation. For e.g.: A specified accuracy of 0.1 would replace all points falling within the 0.1 x 0.1 x 0.1 mm cube by a single point.

b) Trim body: Trim body removes redundant facets by combining facets that are almost in the same plane and generates a smoother polyhedron with fewer facets. For

e.g.: If the threshold angle is set as 2 degrees, neighbouring facets whose change in slope is less than 2 degrees are combined. This is shown in fig (2.6)

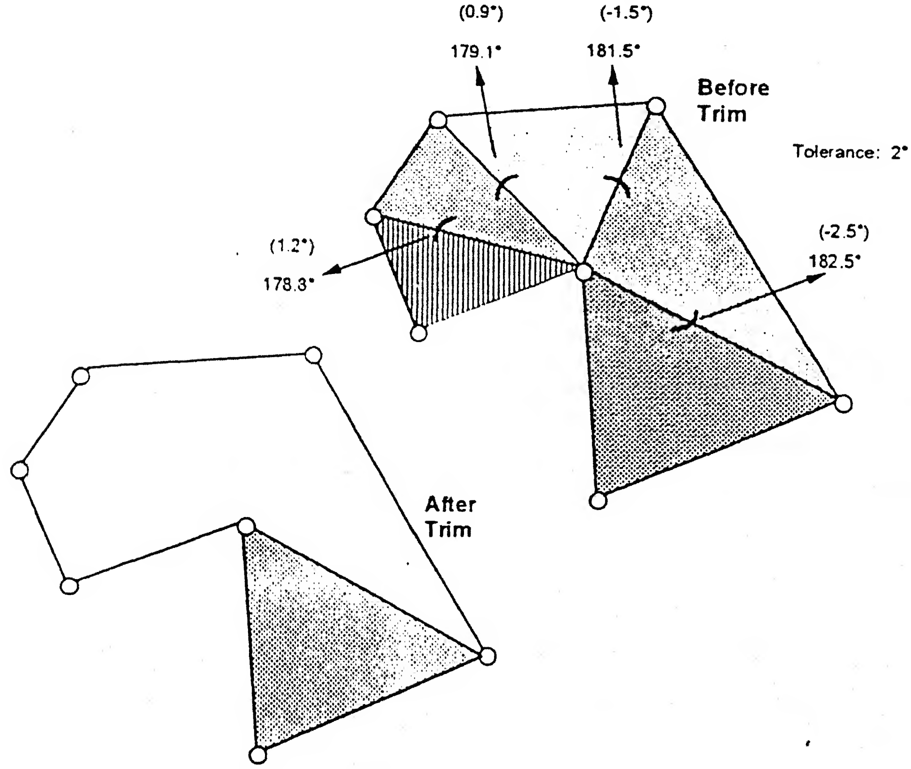


Fig (2.6) Facets before and after trimming

2.3.3 SHOW

The show editor application enables the user to organize a group of actors for a production run on the MPM. A collection of actors with their placement and orientation in the show volume is called a show.

The objective in the show is to place the maximum number of actors within the minimum possible height and volume by fitting them together efficiently. This is because in case of SGC technology, the job height is the only parameter that affects run time, The complexities in X-Y plane do not matter as the whole layer is cured in one go.

The arrangement of show begins by casting the actors to be produced into the show. The user then tries to fit the actors within the minimum possible height by using transformations such as move, rotate, mirror and scale. Actors can be duplicated when more than one copy of a part is required. The user's creativity is

called upon to manipulate the actors to get an optimal show. A show is shown in fig. (2.7)

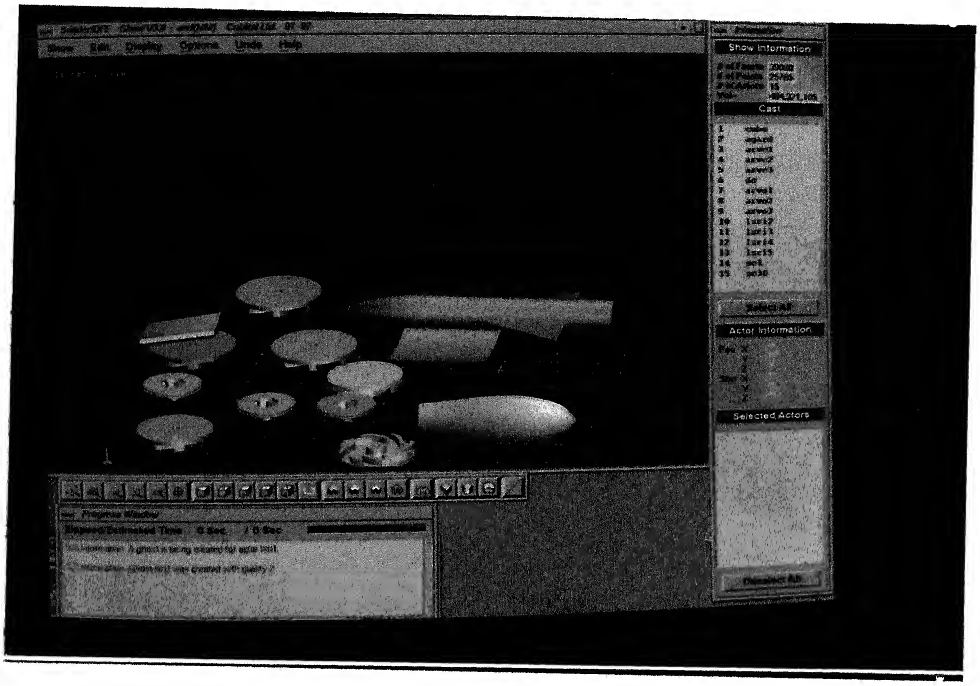


Fig (2.7) Show screen

Once a show is ready, it is saved as a show file and a soli file. The show file is an ASCII file, which consists of Actor names, positions and transformations, applied to the actor. In order to submit the show for production, the group of actors has to be consolidated and replaced with a single compound actor. This is accomplished by using consolidate option and saving the show as a soli file.

2.3.4 PRODUCTION

The production application is used to preview the production file to determine if any actors need to be repositioned and to submit the file for production to MPM.

The slices can be previewed or submitted either live or prerecorded slices can be used. A DFE application called "slicer" is used to slice the file beforehand. The prerecorded slices are generally used when the production file is very complex and the slicing time is more than the time taken for building a layer in MPM, which is about 110 seconds.

Whenever a file is either previewed or submitted, the production verifies whether the consolidated show ca fit into the model tray, taking into account the MPM dimension correction parameters and fence parameters.

a) ***Dimension correction parameters:***

These parameters account for the dimensional inaccuracies in the model building process. The dimension of the mask to be produced is arrived at after applying these corrections to the actual dimensions of the objects. The value of the correction parameters is obtained by running a calibration job. The parameters are:

1) Alpha (x,y): Dimension linear scaling factor

Compensates for linear effects in the process, such as plastic shrinkage.

2) Beta (x,y): Additive factor for edge offset

Compensates for edge effects, such as mask edge definition and edge defocusing due to UV projection.

b) ***Fence parameters:***

Fence is a support built at the outer boundaries of the job to prevent the model slab from collapsing. A production slice showing the fence is shown in fig. (2.8)

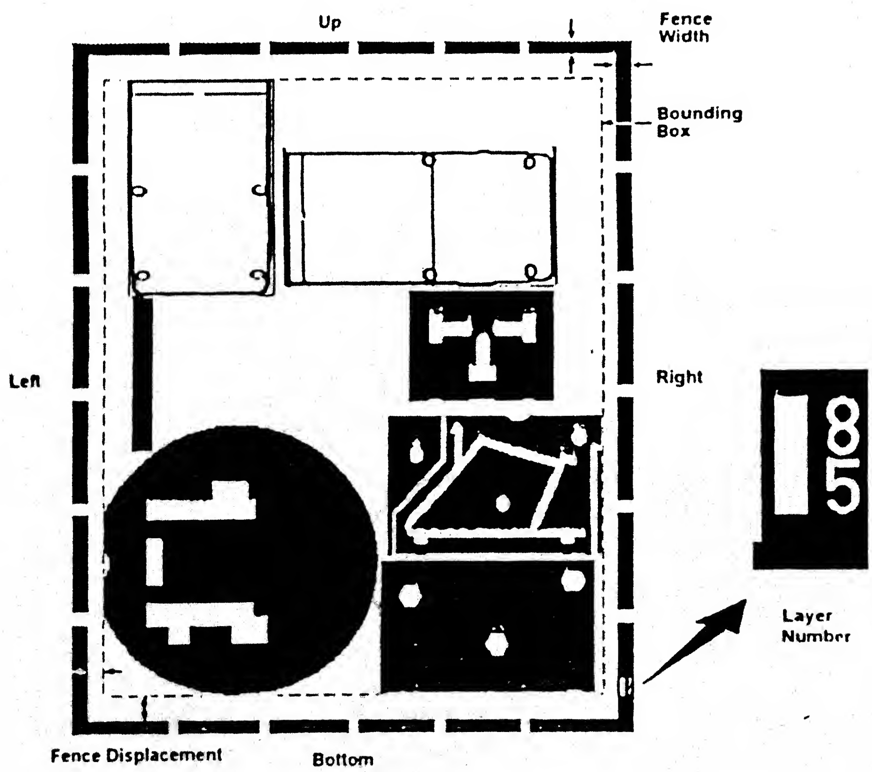


Fig (2.8) Sample slice showing fence parameters

The planks of the fence are made of resin and the spaces between them are filled with wax. The fence parameters are fence width in the left, right, top and bottom of the model tray and fence displacement along the X and Y axes directions.

The fence displacement is the minimum distance that must separate the bounding box of the actors (after applying correction factors) and the fence. The fence parameters can be changed in the show application.

During slicing, the DFE detects and notifies the user about the presence of 'hairs', which are problems that occur because of incorrect facet representation of the actors. Hairs can be of two types: Black hairs, which are usually caused by missing facet and white hairs, which are usually caused by an extra facet. A hair can only run parallel to the Y-axis, from top to bottom following the direction of the rastering process. The hairs can be ignored if they are thin and do not occur in subsequent layers. Otherwise the solution is to either try reorienting the actor or fixing the facet flaws in the academy.

Once the slice preview is deemed to be good, the production file is submitted to the MPM. The production application of the DFE keeps on supplying the slice data to the mask generator of the MPM till the job is finished.

2.4 MODEL BUILDING

2.4.1 MPM software:

A process controller controls all model procedures by coordinating the actions of DFE, MPM and operator's console as shown in fig.(2.9)

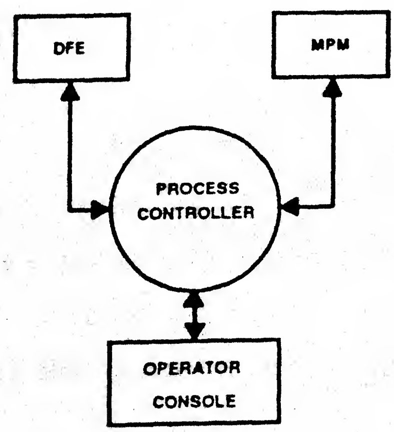


Fig (2.9) Process controller relations

The MPM consists of an 808386 based process controller working under an RMX operating system. 'Solider' is the software package that controls the MPM operations.

The process controller:

- Receives input from the DFE, operator console and MPM units.
- Controls and coordinates all model building procedures.
- Displays operation modes, parameter settings and other job information on the operator console monitor to facilitate operator interaction with MPM.

The MPM software enables the operator to control all model building procedures through the operator's console as the interface. Further details about the MPM software can be obtained from [13].

2.4.2 MODEL BUILDING PROCEDURE

The operator involvement is high in the SGC RP system. The operator should constantly monitor the process to ensure production of quality models. The activities involved in producing a prototype can be separated as Pre-production procedures, Production procedures and post-production procedures.

2.4.2.1 PRE-PRODUCTION PROCEDURES

Certain checks and parameters settings need to be made before submitting the file for production. The pre-production procedures are enlisted below:

1) Raw material verification:

a) Resin: Check the resin drum to see if there is a sufficient supply of resin for the pending job. One resin drum is sufficient for about 2000 layers.

b) Wax: Check the wax level in the wax tank. If level is less than half, add wax blocks to melter. A full wax tank lasts for a full working day. If wax blocks have been added, turn on the melter using the update parameters command. Turn off the melter when there is sufficient melted wax in the tank or when there is no more unmelted wax in wax melter.

2) Functional units verification

a) Compressed air: Ensure that the compressor is switched on and air pressure is 7-8 bars.

b) Water cooling unit: Check water level in water cooling unit and switch on power. The unit takes approximately 20 minutes to cool down to 4 degree Celsius, when MPM is changed to active mode.

c) Chip collector: Visually inspect the chip collector, empty the milling chips if the collector is full.

d) Residual resin collector: Visually inspect the residual resin collector and make sure there is enough room for additional wiped resin. Otherwise, pump the resin into the spent resin barrel.

e) Vacuum generator: Make sure that the vacuum generator main switch and standby button located on the front panel of vacuum generator are on.

f) Cooling plate: Check the underside of cooling plate and make sure there are no traces of wax. If necessary, clean with a plastic scrapper and apply anti-adhesive spray.

g) Wax applicator: Verify that the wax applicator produces a uniform curtain of wax. Place a tray below the applicator ands press the diagnostic spread button. If the curtain is not uniform, the following service procedures can be performed:

1) Clean the wax slit by a shim.

2) Increase the wax pumping pressure.

3) Clean the wax filter with hot water.

4) Increase the temperature of wax hose to melt any solid wax blocking the passage.

h) Milling head: Turn off the milling head power switch. Inspect the hood for blockage and clean if necessary. Clean the milling head cutters with plastic brush if necessary.

i) Wiping unit: Make sure that the air slit is unobstructed. Press the diagnostic button to clear air channels.

j) Resin applicator: Ensure that the resin applicator produces a correct resin curtain. A correct curtain can be produced when air bubbles are absent and resin slit is clean. Use update parameters option to enable bleed mode. Use either the diagnostic button or Alt-1 from the keyboard to perform bleed cycles to remove air from the resin

system. Switch back to resin spread mode. Place a tray below the resin applicator and verify that the resin curtain is uniform.

k) Mask generator: Visually inspect the ion cartridge and make sure it is clean. Gently clean the glass plate with soft tissue paper. Produce standard sample masks using local files. Inspect mask quality. Clean the glass plate and ion cartridge till a good mask is produced.

3) Preparing workpiece base: A 2-3 mm resin base over the PVC plate is necessary before building the model. Adjust the tray height such that 2-3 mm clearance exists between the tray surface and milling head. Use the previous Tag-2 height as reference while moving the tray carriage along Z-direction. The height adjustment has to be made carefully, Otherwise serious damage may be caused to the cooling plate ort milling head.

2.4.2.2 MODEL PRODUCTION

Model production can begin once the workpiece base has been prepared. Before starting a new model batch, the following steps should be followed

1) Set next mask to 1 using the modify option.

2) Set the current layer to Tag-2 using Alt-F10 key combination. Tag-2 is taken as the zero position and used as height reference while model building.

3) Verify that the first exposure time is about 5.6 to 6.0 seconds.

4) Set the mask data source as DFE from update parameters.

5) Submit the production file from the DFE.

6) Begin the model building process by starting the 'long' cycle.

Unlike other RP systems, the responsibility of the operator does not cease once the job is fired. He has to constantly monitor the process and adjust the MPM parameters if necessary. Some of the aspects to be verified during model production are:

1) Inspect quality of image mask. Ensure that there are no stray toner particles sticking to the ion cartridge surface. Clean the underside of the glass plate with tissue paper if the mask quality is not upto mark.

2) Verify that the component layer is not being wiped off after first exposure. The peeling of layer makes a sucking sound at the wiper. The peeling problem can be solve by the following methods:

a) Increasing the exposure time: The layers get peeled off because they do not get enough radiation for polymerisation. So increasing the first exposure time will prevent peeling. But, At the same time increasing the exposure time will cause some portion of light to pass through the black toner areas, thereby partially solidifying the resin, which is outside the layer definition. So ideally the first exposure time should be kept a minimum as possible (about 6 seconds).

b) The other cause for peeling might be that the layer is thicker than what it should be (about 200 microns). A thicker layer will not get sufficient light for polymerisation and thus might peel off. If the model surface is getting milled when it passes from the UV hood to wax applicator, it can be inferred that the layer thickness is more than the required value.

The solution to this problem is to decrease the layer thickness by decreasing the resin pressure or increase the table velocity under the resin applicator in the *traj_mot.dat* file.

c) The third way to overcome peeling problem is by decreasing the wiping pressure.

3) Verify that the resin layer is not thin. If the resin layer is thin, wax layers will be trapped I portions of model where solid resin should be found. If the resin layer is found to be thin, increase the resin pressure or decrease the table velocity under the resin applicator.

4) If the resin layer is not uniform over the table surface, perform resin spread tuning. The tune procedure coordinates the rate of resin flow from the applicator and movement of the model tray. Follow the following procedure for tuning:

a) Activate the diagnostic spread four times.

b) Record the pressure readings in '*resin.log*' file by pressing Alt-M after each spread.

c) Compare the last reading in the first line of the four pressure groups in '*resin.log*'. Copy the pressure group with the lowest reading into ' tune.dat ' file.

d) Make pressure and velocity corrections in '*traj_mot.dat*' if necessary.

e) Press 'F4' to activate Tune command. The tune program takes data from '*tune.dat*' and '*traj_mot.dat*' and saves the output in 'def.mot' file.

The movement of the model tray will now be in accordance to the resin pressure rise characteristic.

5) Inspect underside of cooling plate for adhering wax particles, clean and coat with anti-adhesion spray when necessary.

6) Make sure that wax layer is free from holes and discontinuities. If holes are observed, increase the wax pressure.

7) Check wax supply and add wax blocks to melter if necessary.

8) Empty the chip collector and residual resin collector when they become full.

The MPM produces 100 layers in one batch, which takes about 3 hrs. The 'continue' command should be used to repeat batch production of next 100 layers.

2.4.2.3 POST PRODUCTION PROCEDURE

Once the model production is completed, the workpiece should be removed and cleaned. A trolley is positioned in front of the model tray carriage and the tray is lowered to the level of trolley. The workpiece locking handles are opened and positioning pins are released. The model tray is slided onto the trolley.

The workpiece now needs to be separated from the model tray. First of all, the resin fence on all the four sides are chipped off using hammer and chisel. The workpiece is then separated from the model tray. The workpiece consists of wax slab with hardened resin parts embedded inside it.

Cubital supplies an optional automatic dewaxing machine to quickly remove the wax from the workpiece. The wax is dissolved by spraying a warm citric acid solution through moving nozzles onto the model. The machine dewaxes the model in about 8-10 hrs.

Since IIT-Kanpur has not bought the dewaxing machine, the workpiece is immersed in a sink containing acidic warm water. The workpiece is gently brushed from time to time and the wax gets dissolved slowly. It takes 3 to 10 days for the wax to dissolve depending on the size of the job.

The resin parts are polished with sandpaper to improve surface finish. However Cubital parts unlike Stereolithography parts so not require post curing.

2.5 PROCESS PARAMETERS IN SGC

a) Part orientation: The principle behind part orientation is common to all RP Processes. Since the parts are built layer by layer, part surfaces inclined to the build direction (Z-axis) will suffer from staircase effect. So parts should be oriented in the 'show' such that the major surfaces are either parallel or perpendicular to the Z-axis.

b) Layer thickness: Build time in SGC is determined only by the layer thickness, because horizontal complexities in X-Y plane do not matter. So increasing the layer thickness can reduce the build time, but surface finish will suffer due to stair case effect. Besides this, if the thickness of the layer is increased so should the exposure time of UV light. This causes some portion of UV to pass through the black toner areas in the mask and partially solidifies the resin, which is outside the layer definition.

c) Quality of mask: Quality of mask greatly affects the quality of prototypes. Quality of mask is determined by examining how black the toner portion of the mask is and how white the non-toner portion of the mask is. Ideally, the black portion of the mask should not allow any light to pass through while the white portion should allow all the light to pass. Mask quality is measured by placing an UV meter below a fully transparent mask and a mask fully covered with black toner. The measurements should be within acceptable limits.

d) Exposure time: The first exposure time is also a critical parameter. Ideally it should be set as low as possible taking into account peeling of the layer during wiping. If the exposure time is increased, some portion of UV light passes through the toner covered areas of the mask and partially polymerizes portions of resin that are not meant to be part of the model. The first exposure time is set at around 6 seconds.

e) Resin spread pressure: The resin-spread pressure controls the thickness of the resin layer. As the thickness of the layer is related to exposure time and wiping pressure, the resin pressure should be adjusted carefully. The initial pressure is generally 5 bars.

f) Wiping pressure: Wiping pressure is responsible for removing the uncured resin after first exposure. If it is too low, it may not remove the liquid resin. On the other and, if it is too high, the wiper can peel and suck cured resin also.

g) Room temperature: Room temperature needs to be controlled because it affects the viscosity of the resin. The viscosity of the resin should be within prescribed range to ensure that resin layer of required thickness is spread uniformly over the table. The room temperature is maintained at about 22- 25° C.

h) Dewaxing conditions: The temperature of the water used to dissolve the wax should be within the prescribed value, which is around 40° C. Higher temperatures will affect dimensional accuracy of the model. The dewaxing conditions should be maintained uniform for all models because the correction factors obtained from calibration job depend on the temperature in which the calibration job was dewaxed.

2.6 MATERIAL PROPERTIES

Solider resins are Acrylic based photopolymers specially formulated for use in the SGC system. The resins are non-volatile and insoluble in water. Polymerization may be initiated by heat, oxidizing agents or exposure to UV radiation. The resins are supplied with a polymerization inhibitor, which has a limited lifetime.

Cubital supplies two types of resins: Solimer *G-5601* and Solimer *X611*. The material properties of the resin are given in Table (2.1)

Properties	G-5601	X-611
Viscosity at 32°C	1500	1200
Specific gravity, g/ml	1.1	1.11
Modulus @ 25°C,50% RH, MPa	600	1000
Tensile strength, MPa	27	45
Elongation, %	10	9

Table (2.1) Properties of Solider Resin

Solimer G-5601 was used to make models for the present work.

Chapter 3

IMPELLER PUMPS

AN OVERVIEW

3.1 An Introduction to impeller pumps

Pumps are machines used for lifting liquids from a low level to a high level or for delivering liquids from a region of low pressure to a region of high pressure. They operate by creating a pressure difference between the suction side and delivery side of the moving element, which is the piston in case of reciprocating pumps and impeller in case of rotodynamic pumps.

Impeller or rotodynamic pumps are pumps in which energy is imparted to the liquid by a bladed rotor mounted on a shaft. An impeller pump consists of two principal parts: An impeller which forces the liquid into a rotary motion by impelling action, and the pump casing which directs the liquid to the impeller and leads it away under high pressure.

The impeller consists of backward curved vanes mounted on impeller sidewalls or shrouds. The impeller is mounted on a shaft coupled to a prime mover. The liquid enters the impeller at its center known as the eye and discharges into the casing surrounding the impeller. The pump casing either has a volute or a series of diffusing passages, which transforms the kinetic energy into pressure

3.1.1 Classification of impeller pumps.

Impeller pumps can be classified on the basis of several characteristics. Some of them are enumerated below.

a) On the basis of direction of flow through the impeller, they are classified as *Centrifugal flow*, *axial flow* or *mixed flow* pumps depending on whether the flow direction is radial, axial or a combination of the two.

b) Based on the number of shrouds, the impellers are classified into *closed*, *semi-open* and *open* impellers. In closed impellers, the vanes are covered with shrouds on both

sides, in semi-open impeller the front shroud is removed, while the open impeller is not provided with any shrouds at all.

c) Based on the curvature of vanes, the impeller can have *flat vanes* with no curvature, *singly curved* vanes or *doubly curved* vanes with the suction end being twisted.

d) Based on the number of entrances, they are classified as *single suction* and *double suction* pumps

e) Depending on the number of impellers mounted on the shaft, they are categorized into *single stage* or *multi stage* pumps.

3.2 Pump Characteristics

3.2.1 Energy balance of pumps

The energy input to the pump is the shaft power provided through a prime mover and the energy output is the increased pressure energy of the discharged fluid.

Pump performance is characterized by the following basic quantities:

1) Head
2) Capacity
3) Power
4) Efficiency

Head: The total or effective head is the increase in total energy of the liquid between the inlet and outlet flanges. This increase is equal to the sum of increase in pressure head, the increase in geometric head in the pump itself and the increase in velocity head. These increases are expressed in meters of pumped liquid.

Thus,

Total Head, $H_e = (P_d - P_s)/\omega + h_g + (C_d^2 - C_s^2)/2g$

Where, P_d, P_s are Discharge and suction pressure

C_d, C_s are Discharge and suction velocities

And hg is the vertical distance between pressure tappings for the suction and delivery gauge.

The term $\{(P_d - P_s)/\omega + h_g\}$ is called the manometric head of the pump. The velocity head of the pump is comparatively much less, therefore the manometric head of the pump is equal to the total head for practical purposes.

Capacity: The volume of the liquid pumped per unit time is referred to as Capacity or discharge. It is the rate of flow expressed in terms of liters per hour or m^3/s.

Power: The shaft power is the power input at the pump shaft expressed in HP or kW.

Shaft power, $P = \eta_m \times P_m$

Where, η_m is the efficiency of the motor.

And P_m is the power input to the motor.

Efficiency: The overall efficiency of a pump is the ratio of pump energy output or water horsepower to the power input at the pump shaft.

Efficiency, $\eta = (\omega \times Q \times H) / P$

Where ω is the specific weight in N/m^3

Q is discharge in m^3/s

H is head in m

P is power in watts.

3.2.2 Performance curves

Performance curves are a graphical representation of a pump's behavior under different operating conditions. These curves give a picture of the relation between the discharge and the total head, power and efficiency of a pump whose shaft is rotating at a certain speed.

Characteristic curves show Head, Power and Efficiency of the pump as ordinates and discharge as the abscissa. The characteristics of a typical centrifugal pump is shown in fig. (3.1)

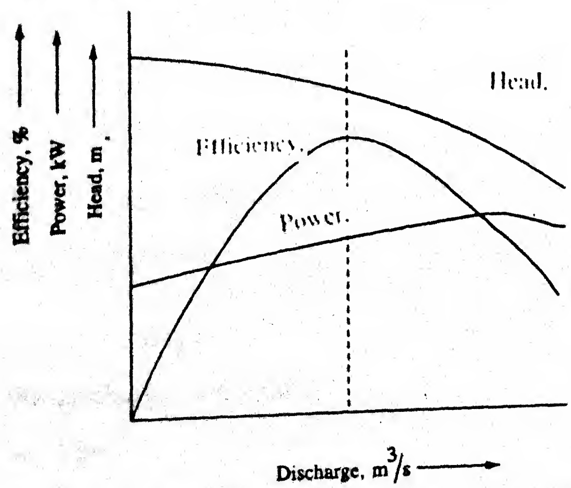


Fig (3.1) Typical characteristics of a centrifugal pump

The characteristics of a pump are obtained by keeping the speed constant and varying the discharge Q by throttling the delivery valve. Head H, Power P and efficiency η are measured or calculated at different discharges. We get the relations

$H = f(Q)$ called the Head-Discharge characteristics

$P = f(Q)$ called the power characteristic

$\eta = f(Q)$ called the efficiency –discharge curve

These three curves from the characteristics of an impeller pump.

The complete characteristics obtained between zero discharge and the full discharge is called as the main characteristic, while the operating characteristics correspond to the best efficiency conditions.

3.3 Similitude and Model testing

Model testing consists of carrying out tests and modifications on a smaller model pump, which is geometrically similar full –size pump. The aim of model tests is to save time and expenses by testing a scaled down version of a larger pump. The results obtained from model tests are subsequently converted into values corresponding to the full size pump.

The theory of dynamic similarity forms the basis of model testing. A full size pump and it's model are said to be dynamically similar, if a) they are geometrically similar, i.e. the shape of vanes, casing etc. are same and b) They are kinematically similar, i.e. similar velocity fields exist in full size pump and it's model. [9]

One of the dimensionless quantities obtained from dimensional analysis of pump is the specific speed. The *specific speed* is an all-important number that characterizes the type of impeller in a unique manner. The specific speed of a pump is the speed of a geometrically similar pump, which produces unit discharge working under unit head. It is given as,

$$N_S = \left(N\sqrt{Q}\right)/H^{3/4}$$

Where N is the speed in rpm

Q is the discharge in m/min

H is head in m.

The head and discharge are measured at the best efficiency point.

Some of the aspects to be considered in model testing [11] are

a) Model speed should be such that the specific speed remains the same as that of the prototype.

b) Head of the model pump should be normally the same as the prototype head, however it can be as low as 80 % of the prototype head.

c) The model pump and prototype pump should be geometrically and kinematically similar.

d) The diameter of the model impeller should not be smaller than 24 cm.

The characteristic quantities of the model pump can be transferred to the full – size pump using the following relationships. [9]

$$Q = Q_m (N/N_m) (d/d_m)^3$$

$$H = H_m (N/N_m)^2 (d/d_m)^2$$

$$P = P_m (N/N_m)^3 (d/d_m)^5$$

Where Q, H, P, N, d are the discharge, head, power, speed and diameter of the full size pump, and Q_m, H_m, P_m, N_m, d_m are the corresponding quantities of the model pump.

The performance of a pump can be refigured from one speed to another by using the Affinity law. The law states that when speed is changed,

a) The capacity varies directly as the speed,

$$Q_1/Q_2 = N_1/N_2$$

b) Head varies directly as square of the speed,

$$H_1/H_2 = (N_1/N_2)^2$$

c) The power required is proportional to cube of the speed.

$$P_1/P_2 = (N_1/N_2)^3$$

Similarly the characteristic quantities can be transferred from a pump of one diameter to a similar pump of different diameter, provided the specific speed of both the pumps remain constant.

3.4 Pump testing principles

Testing of a pump involves experimental determination of characteristic quantities of the pump to determine its performance. The nature of experimental investigation as defined by the density of experimental points, measuring

instruments, test rigs etc depends on the purpose of the investigations. The different purposes of a pump test can be:

a) Design and development: These consist of tests carried out in the factory in the course of developing new pumps. These tests are fairly extensive. Once the performance of a pump is ascertained, the best efficiency conditions are established. Otherwise, constructional modifications are made to improve the performance.

b) Acceptance tests: these tests are carried out at the site of installation. They are undertaken to satisfy the purchaser that the guarantees given by the manufacturers are fulfilled. Such tests comprise determination of efficiency for given head and speed.

c) Scientific investigation: These tests involve investigation of problems such as velocity and pressure distributions at characteristic sections inside the pump, observation of flow fields by introducing coloured particles into the region of flow etc.

The principles and procedures of testing are formulated in standard test codes. These codes give details such as method of testing, instruments to be used, conditions of testing etc. Some of the general principles to be followed in testing are

1) The range of testing defined by the discharges Q_{min} and Q_{max} depends on the purpose of investigation; while testing prototypes it should be fairly extensive while in acceptance tests it is near operating conditions.

2) Testing should take place in conditions approaching as nearly as possible the actual working conditions.

3) Tests should be carried with as many rates of flow as are required to determine the shape of characteristic curves.

4) Measuring instruments should be carefully calibrated.

5) Measuring instruments should be read only when the flow conditions are steady

3.4.1 Measurement of characteristic quantities:

The characteristic quantities of pumps to be measured are: The suction and discharge pressures, the discharge rate, shaft speed and the power absorbed.

a) Pressure measurement

Pressure is measured with elastic pressure gauges such as Bourdon pressure gauges, diaphragm and bellows pressure gauges and vacuum gauge. Usually a

pressure gauge is connected near the outlet flange and a vacuum gauge near the suction end.

Open and differential mercury manometers are also used. In open manometer one end is filled with pumped liquid and the other end is open to the atmosphere. While in differential manometer one limb is connected with the suction flange and the other limb with delivery flange.

b) Measurement of discharge:

Discharge can be measured either indirectly by the weight or volume methods or directly by means of weirs or flow meters.

In the weight method, the amount of liquid that flows into a reservoir in a given interval of time is weighed. The volume flow rate can be calculated from the specific weight of the liquid. In volume method, the volume of liquid that flows into a measuring reservoir in a definite interval of time is measured. This is the most convenient method for open circuit pumps.

Rectangular weirs with or without end contractions may also be used to measure the capacity of a pump. The flow rate in closed –circuit systems are usually measured by means of Venturimeter or orifice meter.

c) Measurement of power:

The power input to pumps can be measured by using mechanical method or electrical method

In the mechanical method, the prime mover shaft is braked and the rpm developed against a known frictional force is measured to calculate the power. The mechanical equipments used to measure power are Prony friction brake, rope brake, torsion Dynamometer etc.

In the electrical method, the power supply to the driving motor is measured by using a voltmeter and ammeter or by using wattmeter. The power input to the pump is then calculated by taking into account the motor efficiency.

d) Speed of rotation:

The shaft speed can be measured by means of a revolution counter and a stopwatch or directly using electrical Tachometer.

Chapter 4

MODEL MAKING AND TESTING

4.1 CAD Modeling of impellers

The first step in the model making process was to create CAD models of impellers with the same vane geometry as in actual impellers. Once the salient dimensions of the impellers were measured, drawings were made and the solid modeling was carried out in *Pro/Engineer* (R. 19) software. *Pro/E* is a high-end CAD/CAM system licensed by Parametric Technology corporation (PTC), USA.

4.1.1 Solid Modeling of Flat vanes:

The Tullu pump impeller used in the present work is of closed type with plain flat vanes. The impeller consists of six flat vanes held between two shrouds. The vanes are arranged such that the discharge angle is 78°. The impeller drawing is shown in fig (4.1)

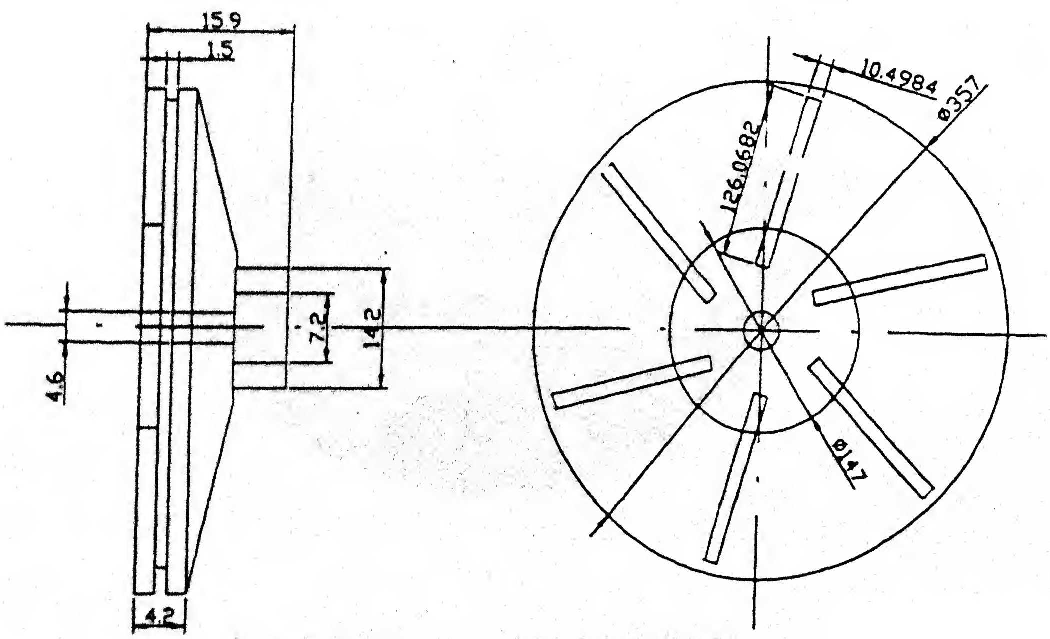


Fig (4.1) Tullu pump impeller drawing

During solid modeling, the front and back shrouds were created first. The cross-sections of the two shrouds were sketched on a reference plane and then the sections were revolved about the impeller axis through 360°. The vane was created using the extrude option. The rectangular shape of the vane was sketched on the inner surface of the front shroud and extruded upto the inner surface of the back shroud. Once a vane was created, a copy of it was made, the copy being rotated through 60°. The other four vanes were created using the pattern option by selecting the 60° dimension as the key pattern direction. Impeller models of different discharge angle were created. The solid model is shown in fig. (4.2)

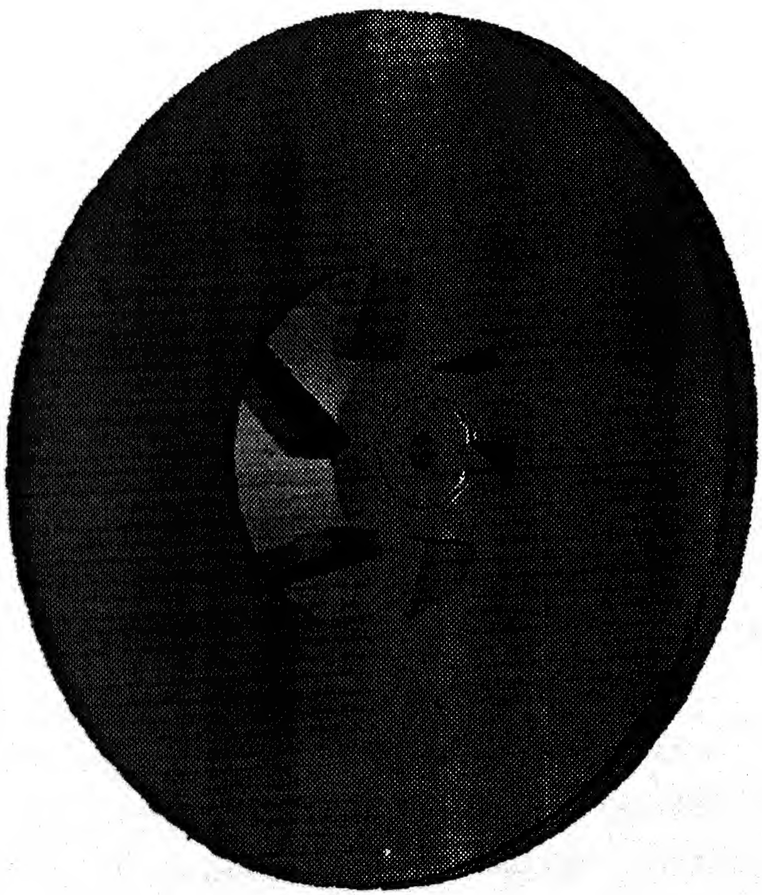


Fig. (4.2) Solid model of Tullu impeller

4.1.2 Solid Modeling of Singly curved vanes:

The Kirloskar pump impeller used in the present work is of semi-open type with singly curved vanes. The impeller consists of eight singly curved vanes attached to the back shroud, such that the discharge angle is 30°. The impeller drawing is shown in fig. (4.3)

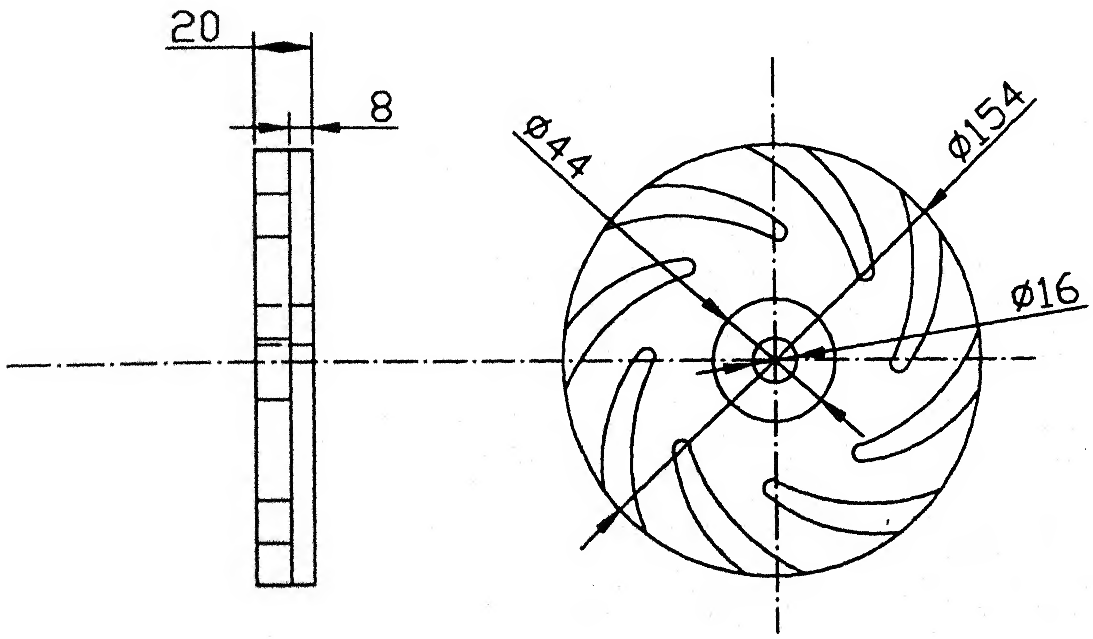


Fig. (4.3) Kirloskar pump impeller drawing

The back shroud was created by sketching the cross-section on a reference plane and revolving the section about the impeller axis through 360°. The profile of the vane was obtained through reverse engineering. The vane of the actual metal impeller was scanned by *'Faro arm* ', a digitizer and a contour curve was fitted to the point cloud using the '*surfacer*' software. The contour of the vane was taken into Pro/E through IGES translation. In Pro/E the vane section was extruded to the required distance to obtain a single vane. The vane was assembled to the shroud by giving the appropriate constraints. A copy of the vane was created, the copy being rotated through 45° from the original. The remaining six vanes were created using the pattern option.

The solid model of Kirloskar pump impeller is shown in fig (4.4)

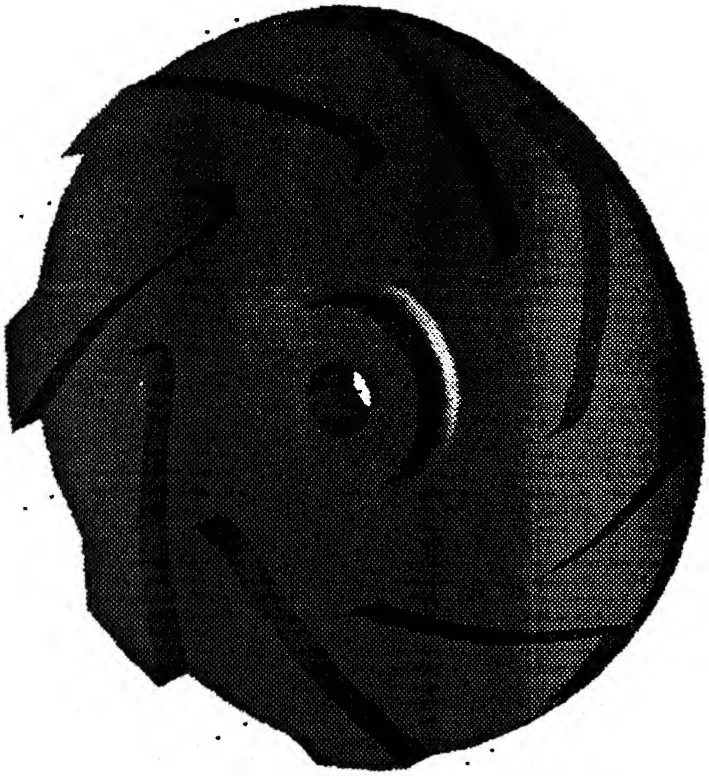


Fig. (4.4) Solid model of Kirloskar pump impeller

4.1.3 Solid Modeling of Doubly curved vanes:

Even though the Kirloskar pump had singly curved vanes, a doubly curved vane was also made for the sake of experimentation.

The shroud was created by sketch and revolve option. The doubly curved vanes were made roughly to the same size as singly curved vanes. The double curvature, with twist of the vanes at suction was achieved by using the blend option in Pro/E. The first section was sketched on the surface of the back shroud, then using the toggle option, the second section was sketched such that inlet side was displaced from the first section. The two sections were blended by giving the required vane thickness.

Once a vane was created, seven other vanes were made using the copy and Pattern options as explained in the earlier section

4.2 Generation of STL file:

Since representation methods used to describe CAD geometry vary from one system to another, a standard interface is needed to convey the geometrical descriptions from various CAD packages to RP systems. The STL (StereoLithography) file is used in almost all RP systems as the *de facto* standard.

The STL file consists of a list of triangular facets representing the outside skin of the object. The facets are described by a set of X, Y and Z coordinates for each of the three vertices and a unit normal vector with x, y and z to indicate which side of facet is inside the object.

A sample portion STL file is shown in fig (4.5).

```
solid print
  facet normal 0.00000e+00 1.00000e+00   0.00000e+00
    outer loop
      vertex  0.00000e+00   0.00000e+00   2.00000e+01
      vertex  0.00000e+00   0.00000e+00   0.00000e+00
      vertex  1.00000e+01   0.00000e+00   2.00000e+01
    endloop
  endfacet
  facet normal 0.00000e+00 1.00000e+00   0.00000e+00
    outer loop
      vertex  1.00000e+01   0.00000e+00   2.00000e+01
      vertex  0.00000e+00   0.00000e+00   0.00000e+00
      vertex  1.00000e+01   0.00000e+00   0.00000e+00
    endloop
  endfacet
........
```

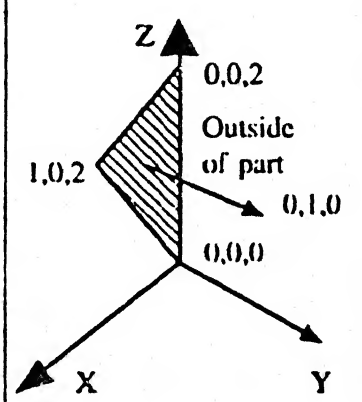


Fig. (4.5) Sample STL file segment

Almost all CAD systems provide options to generate a STL file from a CAD solid model. In Pro/E STL file can be generated from the export option in interface menu. The degree of approximation, which is the degree of coarseness of facets can be controlled through the Chord height and Angle control parameters.

Chord height: It specifies the maximum distance between a chord and a surface. The smaller the chord height specified, lesser is the deviation from actual part surfaces. The lower bound for the chord height is the function of part accuracy and

the upper bound corresponds to the part size. The part size is defined as the diagonal of an imaginary box drawn around the part.

Angle control: Regulates additional improvement to be provided along curves with small radii. Specifically, it tessellates curves that have a radius (r) defined as: r < r_o = part size/10 to achieve a maximum chord height of $(r/r_o)^{\alpha}$ × chord height, where ∝ is the angle control factor.

Thus ∝ = 0 results in no additional improvement for curves with small radii. If the model consists of a surface feature with very small radii relative to its part size, then additional improvement using angle control should be provided. Otherwise these features might have very little definition in the tessellated output.

Although, smaller facets improve the quality of tessellated model, the STL file becomes large. Conversely while larger facets give smaller STL files, the model surface quality suffers. So the tessellation accuracy should be controlled according to the shape of the object to be produced. For e.g. while a sphere would require a large number of facets to approximate its surface, a cube would require very less number of facets.

4.3 Solid Ground Curing (SGC) RP models

The STL files generated in the CAD system were transferred to the Data Front End (DFE). After processing the STL files in the DFE, they were submitted to the Model Production Machine (MPM). The DFE and MPM operations are explained in Chapter 2.

Three RP impellers were made for the Tullu pump. One with the same discharge angle as that of the metal impeller, β=78° and the other two with different discharge angle, β=73° and β=68°.

Similarly three RP impellers were made for the Kirloskar pump. One with the same discharge angle as that of the metal impeller, β = 30°, the second one with β=38° and the third one was an impeller with doubly curved vanes.

The SGC process uses two types of resins, G-5601 and X-611. The X-611 is the produces models of higher strength compared to G-5601. The impeller models for the present work were produced from G-5601.

The RP models along with the metal impellers are shown in fig. (4.6) and fig. (4.7)

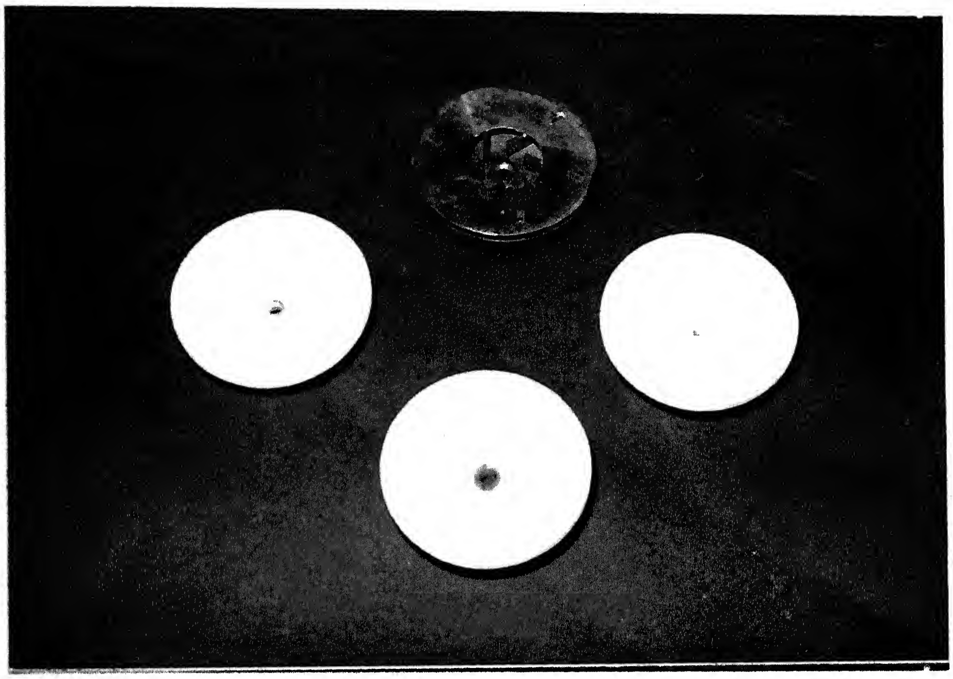


Fig. (4.6) RP models of Tullu pump impeller

Fig. (4.7) RP models of Kirloskar pump impeller

4.4 Pump tests

4.4.1 Pump specifications

Two low head pumps were used for testing. One was a horizontal '*Tullu*' pump with closed impeller and plain flat vanes. The other was a vertical '*Kirloskar*' pump with semi-open impeller with singly curved vanes.

The specifications of the two impellers are given in Table (4.1) below.

Pump	Head, m	Discharge lph	Voltage Volts	Current Amps	Power	Speed rpm
Tullu	3	350	230	0.45	0.025 kW	-
Kirloskar	2	-	415	0.32	0.1 HP	2850

Table (4.1) Pump specifications

4.4.2 Pump test layout

A test setup was made to determine the characteristic quantities of pumps viz. Head, Discharge, Power and efficiency of the pumps. A schematic diagram of the setup is shown in fig (4.8).

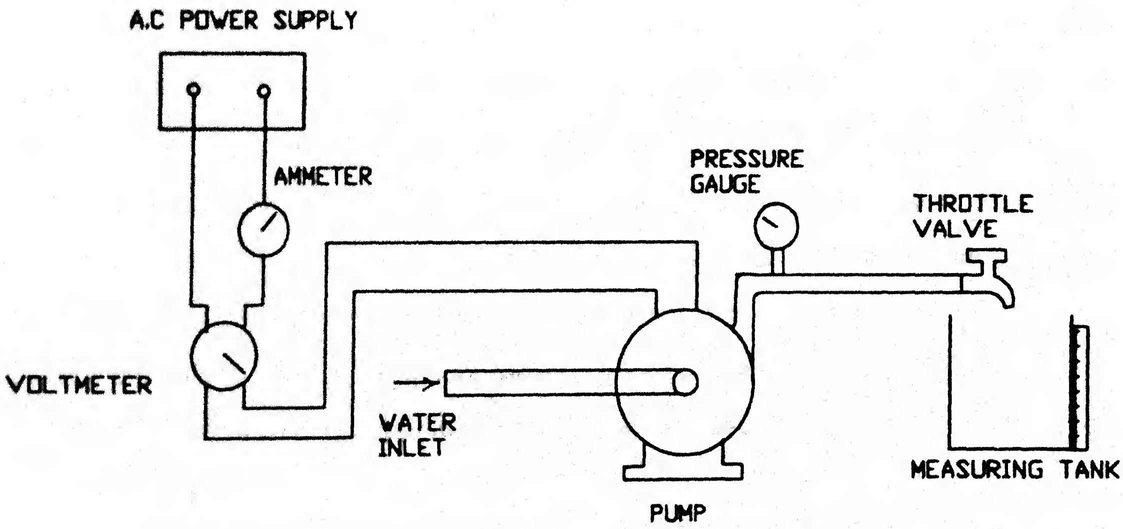


Fig (4.8) Schematic diagram of test layout

The power supply to the pump was taken through an ammeter and voltmeter connected in series and parallel respectively for measuring the power input to the pump. The ratings of voltmeter and ammeter were chosen according to the pump specifications. The input to the pump inlet was given from a source of continuous power supply. In case of the vertical 'Kirloskar' pump, the impeller casing was submerged in water. An outlet pipe was connected to direct the pump discharge to a measuring tank.

A pressure gauge was connected near the pump outlet to measure the head. Negligible suction is created in Tullu pump and the Kirloskar pump needs to be submerged in water, so there was no necessity of having a vacuum gauge at the pump inlet. A throttle valve was connected at the discharge end to control the rate of flow. A measuring tape was attached to the discharge tank to measure the height of water collected for a given period of time.

4.4.3 Pump testing procedure

The pumps were first tested with the metallic impeller and then with RP impellers of different discharge angles. The parameters Head, Power consumption and flow rate were measured at different discharges. 8 – 10 sets of readings were taken between zero discharge and full discharge to obtain the complete characteristics.

To begin with, priming of the pump was done in case of Tullu pump. Power supply was given and the pump was allowed to operate for some time. Then the throttle was completely closed to obtain the series discharge conditions. The readings of the pressure gauge, Voltmeter and Ammeter were noted down. The throttle valve was opened about half a turn. Once the discharge at this opening had stabilized, the height of water collected in the tank for a given period of time was measured along with the Pressure gauge, voltmeter and ammeter readings. The process was repeated till full discharge conditions where the throttle valve was completely opened.

The total head of a pump is the summation of pressure head, velocity head and geometric head of the pump (Vertical distance between inlet and outlet flanges). In Tullu pump, the inlet and outlet pipe were of the same diameter and in Kirloskar

pump, the velocity head ($C_2^2/2g$) was found to be very small compared to pressure head. Therefore, velocity head was neglected in calculations. Also the geometric head of the pump was negligible since the pumps were small. Hence the pressure head was taken to be equal to the Total head in calculations. The power factor was considered as unity for power consumption calculations.

The steps followed in calculations are shown through a sample data:

Sample calculations:

RP impeller of Tullu pump with $\beta = 78°$

Pressure = 0.3 kg/cm^2, Discharge = 305.2 lph, voltage = 250 V, current = 0.46 A

1) Head = pressure $\times$ 10 = $0.3 \times 10 = 3$ m of water

2) Power input to motor, $P_m = V \times I = 250 \times 0.46 = 115$ w

3) Power input to pump, $P_i = P_m \times \eta_m = 115 \times 0.24 = 27.6$ w, where η_m is the motor efficiency = 24 %

4) Discharge in m^3/s = $(305.2 \times 10^{-3}) / 3600 = 8.5 \times 10^{-5}$ m^3/s

5) Efficiency = water power/ input power

$$= (\omega \times Q \times H)/ P_i$$

$$= (9810 \times 8.5 \times 10^{-5} \times 3) / 27.6$$

$$= 8.9\ \%$$

4.5 Finite element analysis (FEA)

Finite element analysis (FEA) is a technique that can predict deflection and stress on a structure. FEA divides the structure into a grid of 'elements' connected to each other at 'nodes', which form a model of the real structure. Each of the elements is a simple shape such as square or triangle for which governing equations are written in the form of stiffness matrix. The unknowns for each element are the displacements at the node points. The FE program assembles the element stiffness matrices to form the global stiffness matrix for the entire model. The stiffness matrix is solved for the unknown displacement, given the known forces and boundary conditions. From the displacements at the nodes, the stresses in each element can then be calculated.

Finite element analysis was carried out to determine the maximum stress developed in the vanes and shrouds of the impeller. The aim was to find out the

performed using the simulation tool of I-DEAS Master series software. I-DEAS is a popular CAD/CAM system developed by SDRC, USA.

The steps involve in FEA of a part are:

1) Solid modeling
2) Meshing
3) Applying boundary conditions.
4) Model solution
5) Post processing

Solid modeling: In FEA a solid model of the part to be analyzed needs to be created first. But in this case, there was no need to create a solid model, as the model created for RP already existed. The solid model of the impeller was imported into I-DEAS from Pro/E through IGES translation.

Meshing: I-DEAS has the options of generating a mesh manually by creating nodes and elements or through automatic mesh generation. Automatic mesh generation was done for this exercise. The material properties of the G-5601 resin such as the Young's Modulus, Tensile strength, Poisson's ratio etc were entered for the FE model. Linear tetrahedron element with element length of 50 was selected for meshing. The FE model consisted of 15289 elements.

Boundary conditions: Boundary conditions include Restraints and Loads. The required degrees of freedom can be given according to physical object being modeled. The forces involved in a pump are the pressure force and the centrifugal force. The pressure force was taken to be 0.3 kg/cm^2, which was the pressure obtained when maximum head developed at zero discharge conditions. During initial FEA trials, the centrifugal force of the vanes was found to have negligible effect compared to the pressure force. Therefore, for simplicity, the centrifugal force was neglected for further analysis.

As boundary conditions, the inner surface of the back shroud was completely restrained, and a uniform pressure of 30 mN/mm^2 was applied on the vane surface

and inner surface of shrouds. The analysis was done on a single vane channel, taken to be the representative of the whole impeller.

Model Solution and post processing: The FE model was solved using the model solution task of the I-DEAS Simulation tool. Post processing helps visualization of results in a customized fashion. The stress plots were obtained from the post-processing task.

The post-processing module of I-DEAS is shown in fig (4.9)

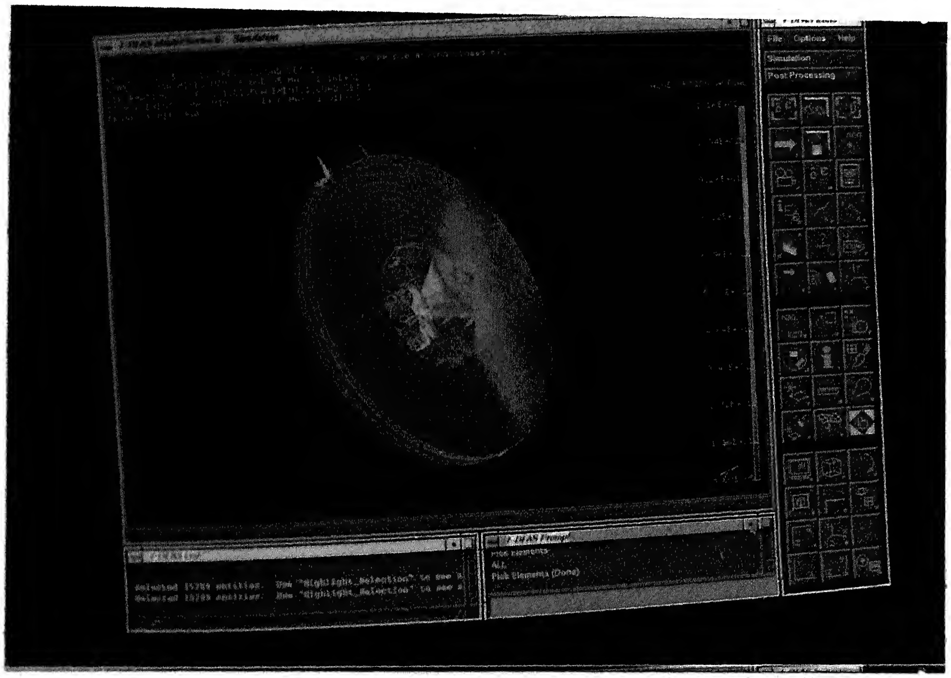


Fig. (4.9) Post processing task in I-DEAS

The FE model was solved using iterative method and the stress plots were obtained from post processing.

Since the pressure forces encountered in the present pump test conditions gave a high safety factor of safety (about 15), the FEA was further continued by gradually increasing the pressure force till a factor of safety of about 1.5 was obtained.

Chapter 5

RESULTS AND DISCUSSIONS

5.1 Pump test results

Performance tests were conducted on Tullu pump and Kirloskar pump for comparing the characteristics of actual metal impeller with RP impeller. The results of these tests have been discussed in the following sections.

5.1.1 Tullu pump results

The Tullu pump was tested with the metal impeller and an identical RP impeller with discharge angle, $\beta = 78°$. Experiments were also conducted with RP impellers of lower discharge angles, $\beta = 73°$ and $\beta = 68°$.

The test results i.e. the values of the characteristic quantities are given in Tables (5.1), (5.2), (5.3) and (5.4)

Sl. No.	Discharge Q in lph	Head m	Power kW	Efficiency %
1	0.0	3.2	0.0266	0.0
2	297.4	2.8	0.0278	8.2
3	325.2	2.4	0.0289	7.3
4	354.0	2.0	0.03	6.4
5	398.8	1.6	0.0315	5.5
6	421.3	1.2	0.0315	4.4
7	466.5	1.2	0.0315	4.8
8	491.0	0.8	0.033	3.3
9	537.9	0.4	0.033	1.8
10	574.3	0.4	0.033	1.9

Table 5.1 Characteristic quantities of Tullu pump With Metal impeller, $\beta = 78°$

Sl. No.	Discharge Q in lph	Head m	Power kW	Efficiency %
1	0.0	3.2	0.0278	0.0
2	305.2	3.0	0.0278	8.9
3	337.4	2.6	0.03	7.9
4	376.3	2.0	0.03	6.8
5	410.5	1.6	0.029	6.2
6	426.4	1.2	0.0315	4.4
7	458.3	0.8	0.033	3.1
8	486.2	0.4	0.033	1.6
9	527.4	0.4	0.033	1.7
10	564.2	0.4	0.034	1.8

Table 5.2 Characteristic quantities of Tullu pump

With RP impeller, $\beta = 78°$

Sl. No.	Discharge Q in lph	Head m	Power kW	Efficiency %
1	0.0	3.0	0.0278	0.0
2	300.5	2.4	0.029	6.8
3	326.8	1.6	0.029	4.9
4	352.4	1.2	0.03	3.8
5	386.9	1.2	0.029	4.4
6	402.3	0.8	0.0314	2.7
7	428.4	0.4	0.0314	1.4
8	456.7	0.4	0.033	1.5
9	493.1	0.4	0.033	1.6
10	527.8	0.4	0.033	1.7

Table 5.3 Characteristic quantities of Tullu pump

With RP impeller, $\beta = 73°$

Sl. No.	Discharge lph	Head m	Power kW	Efficiency %
1	0.0	2.8	0.029	0.0
2	292.5	2.4	0.029	6.6
3	328.6	1.6	0.03	4.7
4	354.1	1.6	0.0314	4.9
5	376.9	1.2	0.0314	3.9
6	394.5	0.8	0.0314	2.7
7	427.8	0.8	0.033	2.8
8	461.4	0.4	0.033	1.5
9	492.3	0.4	0.0314	1.7
10	519.1	0.4	0.033	1.7

Table 5.4 Characteristic quantities of Tullu pump

With RP impeller, $\beta = 68°$

The characteristic curves of Tullu pump with metal and RP impellers are shown in fig. (5.1), fig. (5.2), fig.(5.3) and fig.(5.4)

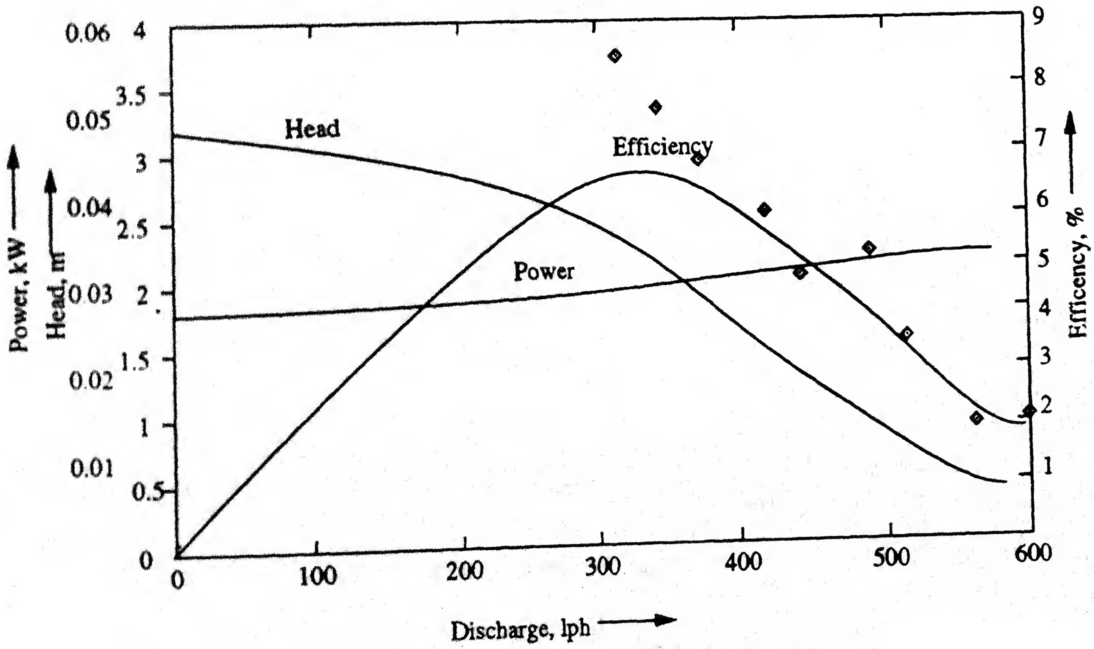


Fig.(5.1) Characteristic curves of Tullu pump

With metal impeller, $\beta = 78°$

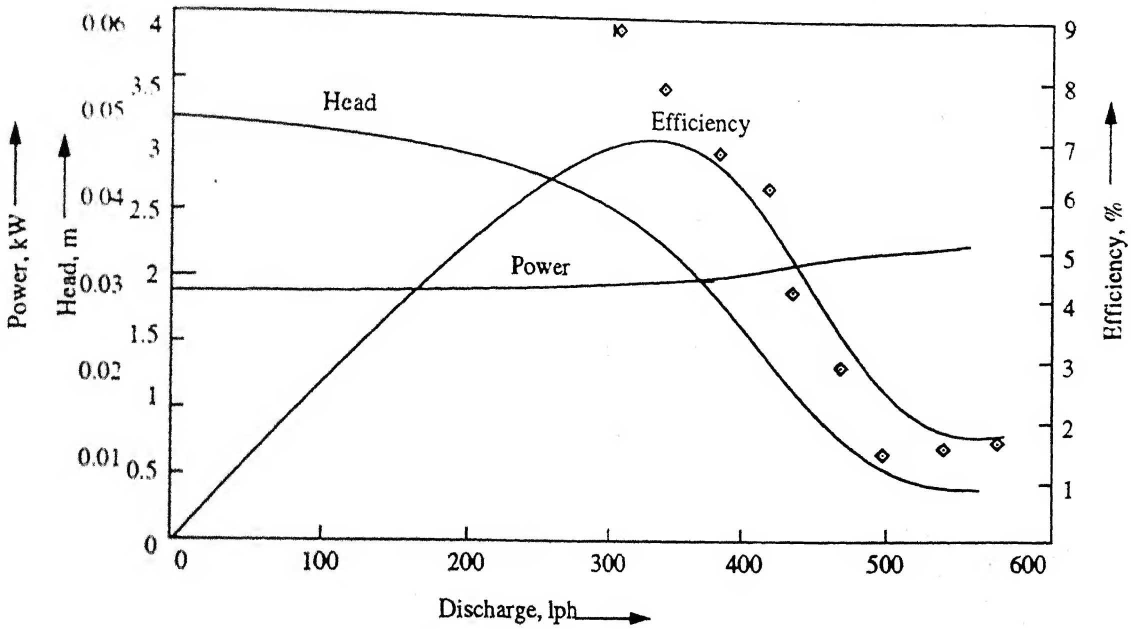


Fig.(5.2) Characteristic curves of Tullu pump
With RP impeller, $\beta = 78°$

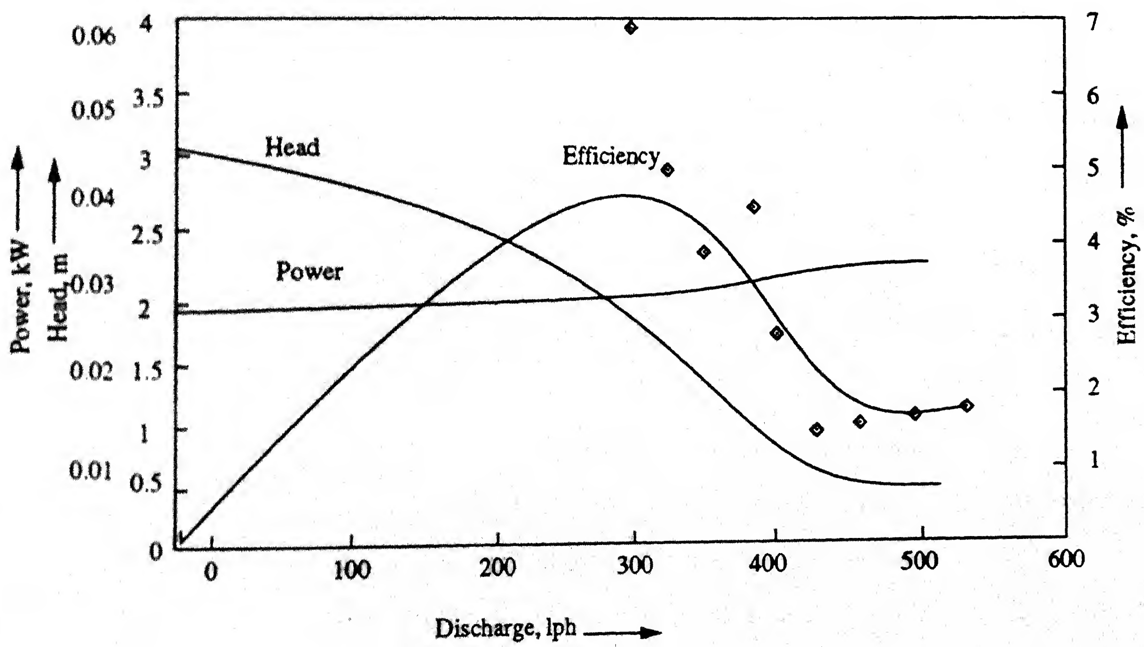


Fig.(5.3) Characteristic curves of Tullu pump
With RP impeller, $\beta = 73°$

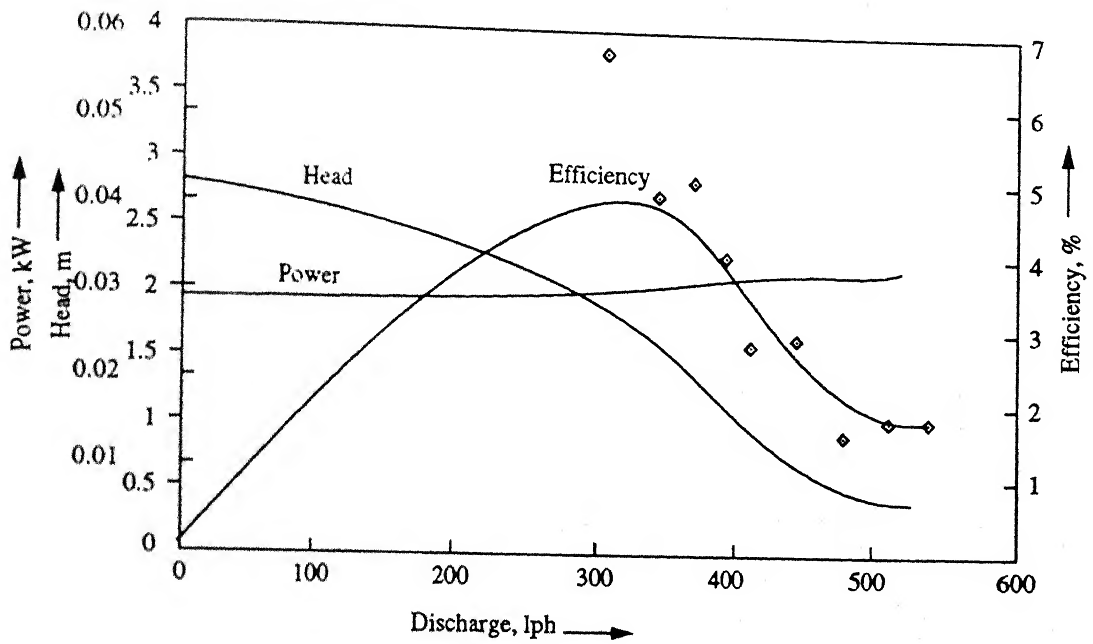


Fig.(5.4) Characteristic curves of Tullu pump

With RP impeller, $\beta = 68°$

Even before comparing the characteristic curves, it is to be noted that the RP impellers have withstood the pump forces inspite of having thin shrouds (about 2 mm thick). Thus, RP models can be considered viable for hydrodynamic testing under low head test conditions from the strength point of view.

Fig. (5.1) and Fig.(5.2) give the characteristic curves for metal and RP impellers respectively. It can be seen that the power consumption increased marginally with discharge. However, the head developed dropped drastically from zero discharge to full discharge conditions. The maximum efficiency or best operating condition is found to be at a discharge of about 350 lph. From these two graphs, it can be seen that the head, power and efficiency curves of the RP impeller follow the same trend as that of metal impeller. Both the graphs also give almost identical best efficiency conditions. Thus it can be concluded that the vane geometry created in the CAD system was faithfully reproduced by the Solider RP system. This makes the SGC RP process an attractive proposition for creating impeller prototypes for centrifugal pump testing.

Fig (5.3) and Fig (5.4) show the performance characteristics of RP impellers with smaller discharge angles than the actual metal impeller. The head at zero discharge in impeller with $\beta = 73°$ was found to be less compared to the head developed by the actual impeller in identical conditions. The head decreased further with the impeller with $\beta = 68°$. But, all impellers gave almost similar heads at higher discharges.

It can be seen that RP impellers with smaller discharge angles have produced lesser heads, which is in accordance with theoretical expectations.

5.1.2 Kirloskar pump results

Performance tests were conducted on the Kirloskar pump to compare the characteristics of the metal impeller ($\beta = 30°$) with a RP impeller of same discharge angle. In addition to these, tests were conducted on a singly curved RP impeller with $\beta = 38°$ and a doubly curved RP impeller.

The experimental results i.e. the values of characteristic parameters are tabulated in Tables (5.5), (5.6), (5.7) and (5.8)

Sl. No.	Discharge lph	Head m	Power kW	Efficiency %
1	0.0	2.0	0.106	0.0
2	343.6	1.6	0.106	1.4
3	414.2	1.4	0.11	1.42
4	472.8	1.2	0.115	1.33
5	559.1	0.9	0.115	1.10
6	613.5	0.8	0.119	1.10
7	680.7	0.6	0.115	0.93
8	741.3	0.6	0.119	1.10

Table 5.5 Characteristic quantities of Kirloskar pump

With metal impeller, β=30°

Sl. No..	Discharge lph	Head m	Power kW	Efficiency %
1	0.0	1.9	0.106	0.0
2	363.6	1.6	0.11	1.43
3	402.8	1.4	0.11	1.45
4	461.9	1.2	0.115	1.30
5	534.1	1.0	0.119	1.20
6	587.2	0.8	0.119	1.07
7	663.4	0.6	0.119	0.9
8	720.7	0.6	0.119	0.98

Table 5.6 Characteristic quantities of Kirloskar pump

With RP impeller, $\beta = 30°$

l. No.	Discharge lph	Head m	Power kW	Efficiency %
1	0.0	2.6	0.106	0.0
2	373.8	2.0	0.106	1.9
3	410.2	1.6	0.11	1.6
4	480.6	1.4	0.115	1.59
5	568.9	1.4	0.119	0.8
6	611.4	0.8	0.119	1.1
7	672.1	0.6	0.11	0.9
8	746.3	0.6	0.119	1.0

Table 5.7 Characteristic quantities of Kirloskar pump

With RP impeller, $\beta = 38°$

Sl. No.	Discharge lph	Head m	Power kW	Efficiency %
1	0.0	2.8	0.106	0.0
2	393.8	2.4	0.11	2.3
3	420.6	2.0	0.11	2.1
4	503.4	2.0	0.11	2.5
5	579.3	1.6	0.115	2.2
6	635.2	1.4	0.115	2.1
7	701.7	1.2	0.119	1.9
8	769.1	0.8	0.119	1.4

Table 5.8 Characteristic quantities of Kirloskar pump
With RP impeller, doubly curved vanes

The characteristic curves of Kirloskar pump with metal and RP impellers are shown in fig.(5.5), (5.6), (5.7) and (5.8).

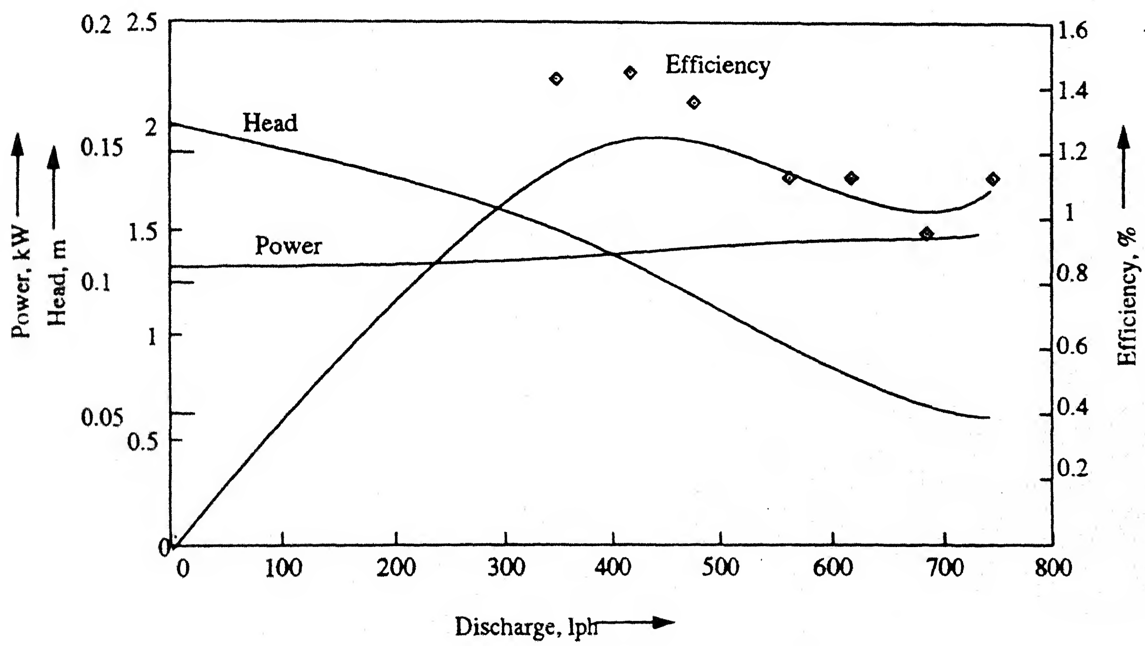


Fig.(5.5) Characteristic curves of Kirloskar pump
With metal impeller, β = 30°

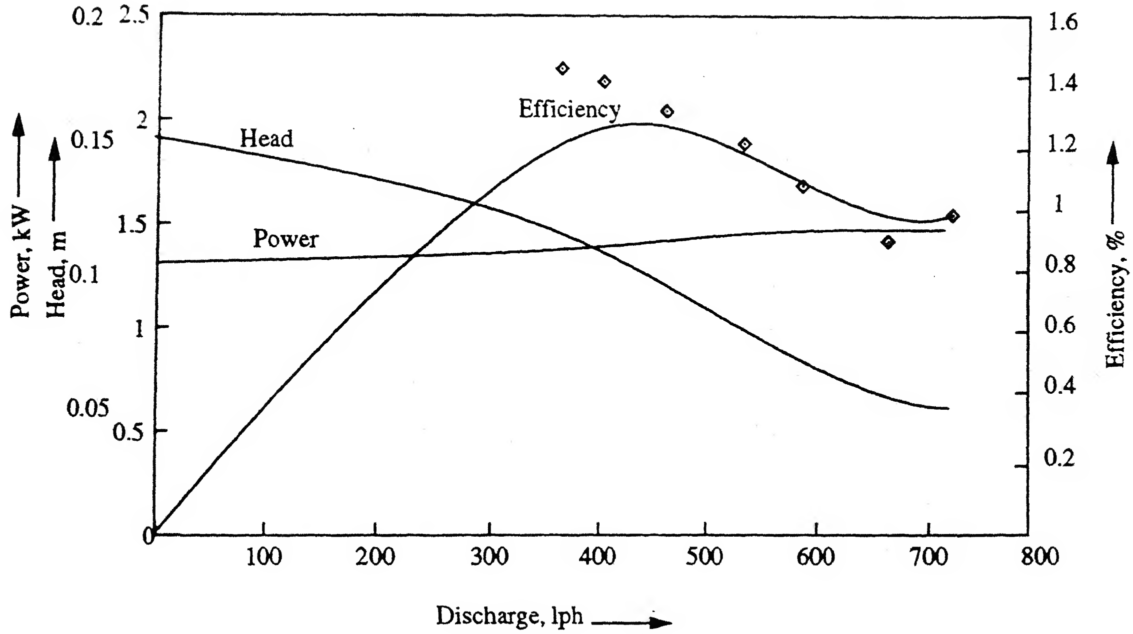


Fig.(5.6) Characteristic curves of Kirloskar pump

With RP impeller, $\beta = 30°$

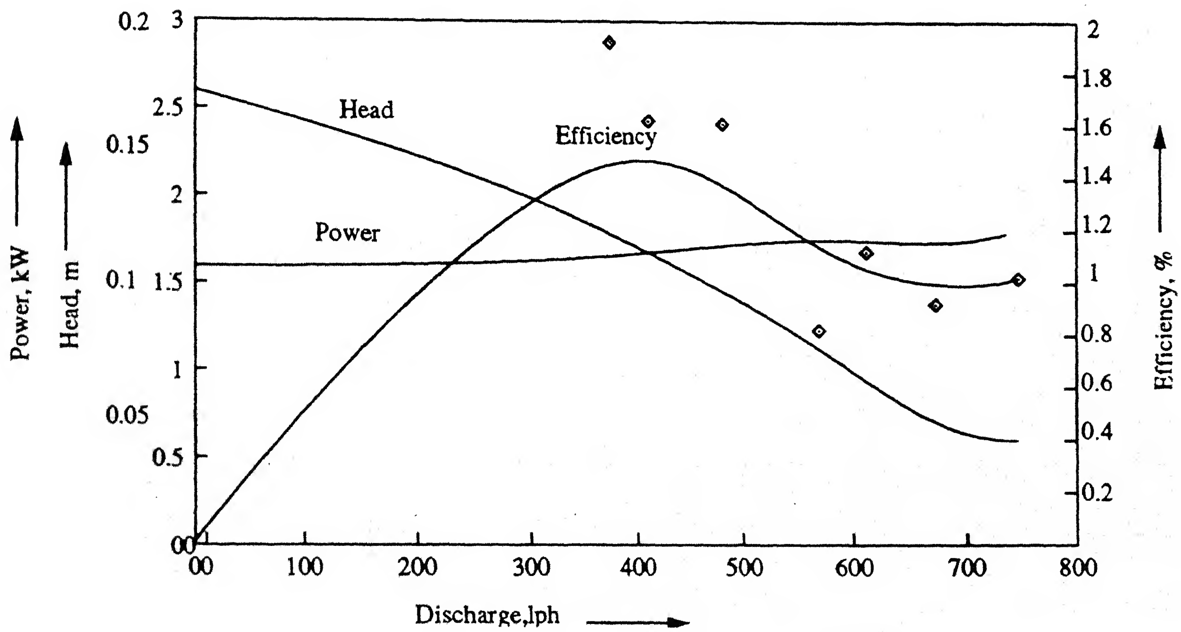


Fig.(5.7) Characteristic curves of Kirloskar pump

With RP impeller, $\beta = 38°$

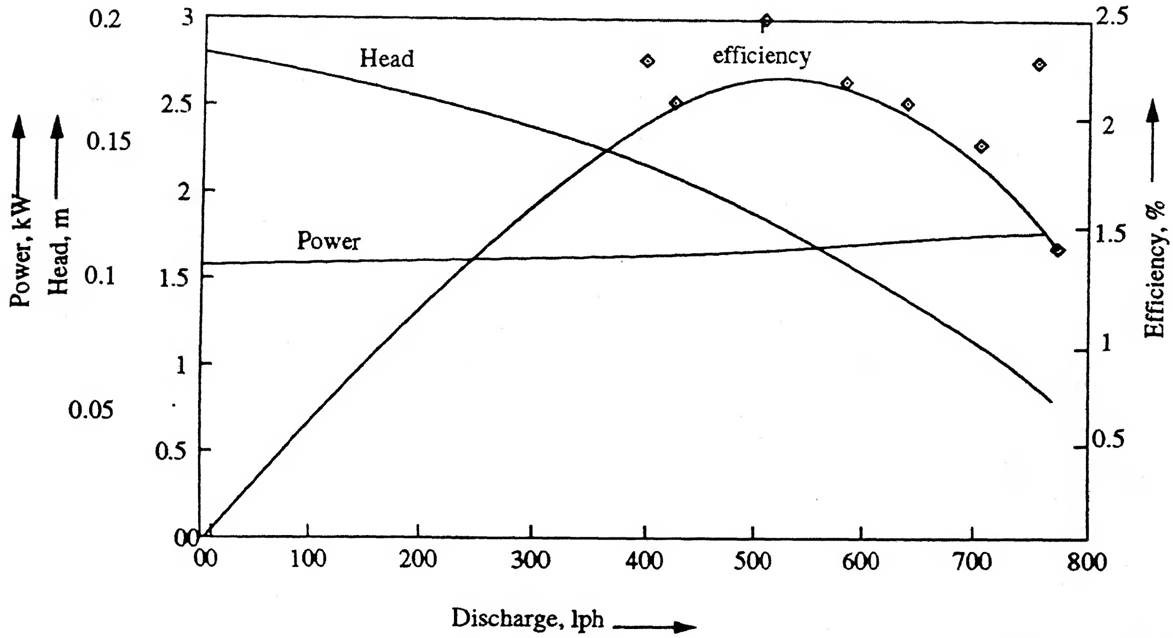


Fig.(5.8) Characteristic curves of Kirloskar pump
With RP impeller, doubly curved vanes.

Since the vanes and shroud of the Kirloskar pump impellers were quite thick, they were expected to withstand the pump forces. Experimental results have proved likewise. Fig.(5.5) and (5.6) give the characteristic curves for the metallic and RP impellers with discharge angle, $\beta = 30°$. It can be seen that the rate of increase in power consumption with increasing discharge was less. However, the head dropped considerably at higher flow rates. The best efficiency point was found to be at a discharge of about 450 lph.

Also from, fig (5.5) and (5.6), it can be seen that the characteristics of the RP impeller are almost similar to that of actual metal. From fig (5.7), it can be seen that the RP impeller with higher discharge angle, $\beta = 38°$ gave higher heads compared to the impeller with $\beta = 30°$. This is in accordance with theoretical predictions. The doubly curved impeller gave the highest head as shown in fig (5.8)

5.2 Finite element analysis (FEA) results

The FEA was carried out to determine the maximum stress developed in the vanes and shrouds of the impeller under test conditions. The final aim was to deduce the limiting test conditions.

The pressure force of 0.03 MPa, which was the maximum pressure encountered in the pump tests, gave a maximum stress of 1.83 MPa. The stress plot is shown in fig.(5.9). The maximum stress was found at the edges where the vane is connected to the shrouds. Therefore failure might occur by shearing of the vanes from the shrouds, at stresses higher than the strength of the resin material.

The present pump test conditions gave a high factor of safety of about 15, since the maximum stress developed was 1.83 MPa, while the material strength is 27 MPa. Therefore FEA of the model was continued further by gradually increasing the pressure force till a factor of safety of 1.5 was obtained. This was done to determine the upper limit of pressure that the impeller can withstand. Also, since the pressure force is directly related to head, the limiting value of head under which the RP impeller can be tested can also be deduced.

The results of FEA test are given in table (5.9).

Tensile strength = 27 MPa

Sl No.	Head m	Pressure MPa	Max. stress MPa	Factor of Safety
1	3	0.03	1.83	14.8
2	4.5	0.45	2.53	10.7
3	6	0.06	3.87	7.0
4	8	0.08	4.50	6.0
5	10	0.10	6.89	3.9
6	15	0.15	9.67	2.8
7	20	0.20	12.90	2.1
8	25	0.25	16.10	1.7
9	30	0.30	19.30	1.4

Table (5.9) Factor of safety at different heads.

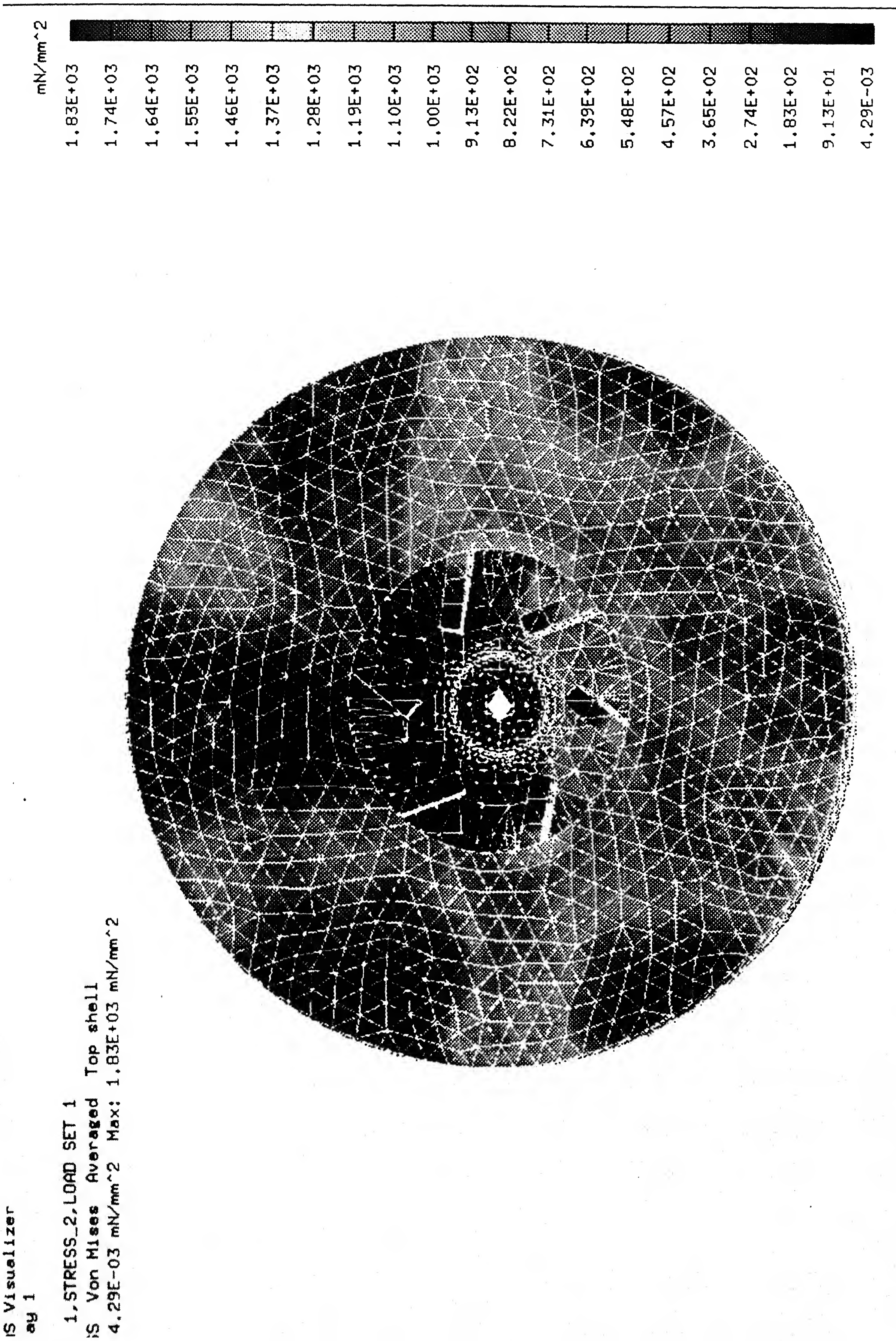


Fig. (5.9) Stress plot for the pump test conditions.

The factor of safety at various heads for the RP impeller is shown in fig (5.10)

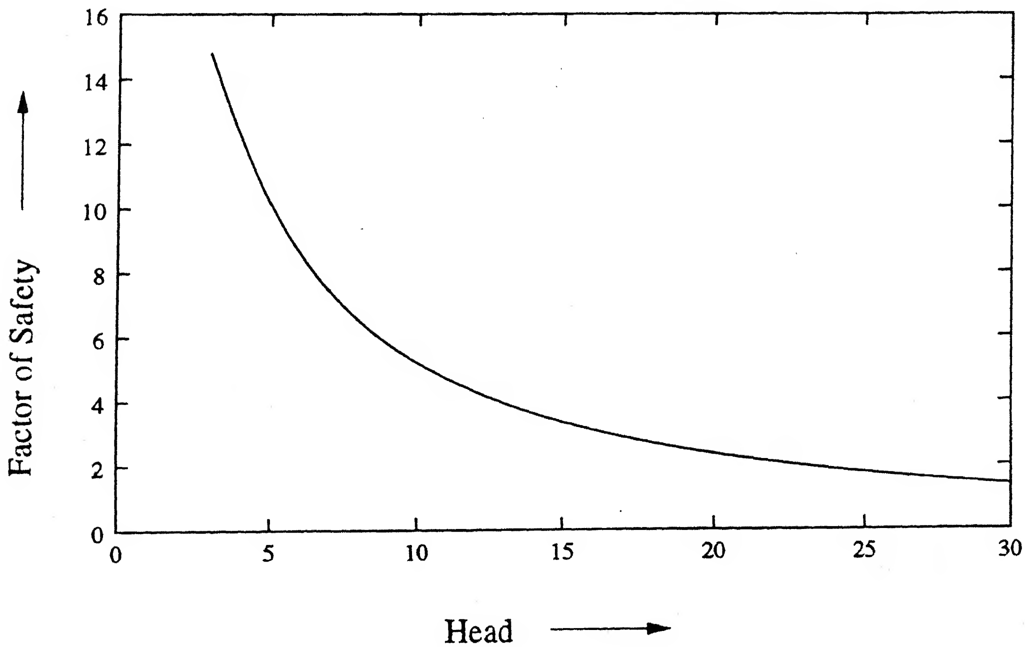


Fig (5.10) variation of head with factor of safety

Thus it can be concluded that RP impeller used in present work can be used for testing pumps within a maximum head of 30 m.

Chapter 6

CONCLUSIONS

6.1 Technical Summary

The twin objectives of the present work, viz.

a) Establishing the Solid ground curing (SGC) RP system at IIT-Kanpur

b) Studying the feasibility of using the prototypes produced by the SGC system for hydrodynamic analysis in the form of centrifugal pump testing

have been fulfilled successfully.

The Solider 4600 RP system has some unique capabilities compared to other RP systems, but it also is the most complex and difficult to operate RP machine. During the course of this work, a number of industrial prototypes have been produced successfully. The Solider system builds a model by effective coordination of various data processing and model building units. The various parameters to be controlled for producing quality models have been studied extensively. It has been found that the quality of mask, the first UV exposure time and the layer thickness are the most critical parameters in model production.

The feasibility of using SGC-RP models for hydrodynamic analysis has been examined by testing RP impellers on centrifugal pumps. Two low head pumps, a horizontal Tullu pump and a vertical Kirloskar pump were selected for testing. CAD models of the impellers were created and RP models were produced with exactly the same vane geometry as the actual metal impellers. Performance tests were conducted on the pumps and pump characteristics for both the metal and RP impellers were determined.

The RP impellers were strong enough to withstand the pump forces, despite having thin shrouds in case of Tullu pumps. Thus it can be concluded that RP models can be used for low head hydrodynamic testing from the strength point of view. The characteristics of RP impellers were found to be similar that of actual metal impeller. Thus it can be said that the Solider RP system correctly reproduced the CAD models into physical prototypes and also that the RP impeller did not undergo any distortions during testing. Variation in discharge angles of the impellers

gave characteristic curves in accordance with theoretical expectations. Also, FEA of impellers was carried out to determine the maximum stress developed in the impeller under the pump test conditions. It was found that the RP impeller used in present work could work under a maximum head of 30 m.

Since the traditional ways of making impeller prototypes is cumbersome, pump manufacturers can use the RP technology to develop impeller prototypes quickly and accurately.

In conclusion, the SGC RP process is a viable proposition for producing impeller prototypes for centrifugal pump testing.

6.2 Suggestions for Solid ground curing process

The 'Solider' is a high end RP system with some unique capabilities like high throughput, ability to produce assemblies, no support structure required, no post-curing etc. At the same time it is one of the most difficult to operate RP systems, simply because of the large number of subsystems and units involved in model production. Some suggestions for the process are given below.

- The 'Solider' machine is a workhorse; the more it runs, the better it works. It should not be kept idle for a long time. Therefore even if there are no jobs to be produced, the subsystems of the units such as Mask generator, resin applicator, wax applicator etc should be operated from time to time.
- The wax unit is the most problematic of all the units. So, when the machine is idle for too long, a few wax spreads should be tried out once in a few days to ensure proper functioning of the unit. The machine should be kept in standby mode always to ensure that the wax does not solidify.
- It is suggested that the first UV exposure time be kept as low as possible during model production. The method is to go on decreasing the exposure time till the layer starts to peel off. The exposure time can then be set at the next higher level
- It is suggested to have a dewaxing machine with temperature control and some means for agitation for faster wax removal. The present manual method for dissolving wax is very slow. It does not make sense to get a part from the RP machine in about 10 hours, but wait for about a week for postprocessing finish.

6.3 Scope for future work

- The pumps tested with RP impellers in the present work were of very low heads. Therefore to strengthen the claim that RP models can be used for impeller prototype development, further tests on medium and high head pumps are required.
- As an extension of this work, testing of turbines such as pelton wheel buckets can be carried out. Since in a pelton wheel bucket, the jet should break in an exact manner, the surface of the RP model can be coated with a metal spray if required for better surface finish.
- The other possible application in hydrodynamics could be the design of hull of a ship. Various shapes of the hulls designed in the CAD system can be transformed into physical prototypes by Rapid prototyping. These models can then be used to study the streamlines, which could help in arriving at a better hull design.

[1] Chua Chee Kai & Leong Kah Fai, "Rapid Prototyping: Principles and applications in manufacturing", John Wiley & Sons, Inc, 1997

[2] Paul F. Jacobs, "Rapid Prototyping & Manufacturing"

[3] D.Kochan & C.K.Chua, "State-of-the-art and future trends in advance Rapid Prototyping & manufacturing", *International journal of Information Technology*, Vol. 1, No.2, 1995

[4] J.P.Kruth, "Material Incress Manufacturing by Rapid Prototyping Techniques", *CIRP Annals*, Vol.40 No.2 1991

[5] Cubital's Solider 4600 Users Manual

[6] Michael E. Mortenson, "Geometric Modeling", John Wiley & Sons.

[7] Pro/E Part modeling user's guide.

[8] IDEAS-Master Series Student Guide.

[9] Stephen Lazarkiewicz & Adam T. Troskolanski, "Impeller Pumps", Pergamon Press

[10] A. J. Stepanoff, "Centrifugal and Axial flow pumps", John Wiley & Sons, Inc

[11] Val S. Lobanoff and Robert R. Ross, "Centrifugal pumps Design and application", Gulf publishing company, 1985.

[12] Jagdish Lal, "Hydraulic Machines", Metropolitan book Co. Pvt. ltd., 1977

[13] L.Srinivas, "Application of SGC-RP Technique For Development of Aerodynamic models", M.Tech Thesis, IIT-Kanpur, 1999